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Rufo et al.

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(54) **AQUATIC VEHICLE**

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Related U.S. Application Data

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(51) **Int. Cl.**

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B63H 11/00	(2006.01)
F16F 3/00	(2006.01)
B63B 7/08	(2006.01)
B63H 1/36	(2006.01)
F16F 1/02	(2006.01)

(52) **U.S. Cl.**

CPC . ***B63G 8/08*** (2013.01); ***B63B 7/085*** (2013.01); ***B63H 1/36*** (2013.01); ***B63H 11/00*** (2013.01); ***F16F 1/025*** (2013.01); ***F16F 3/00*** (2013.01); *Y02T 70/56* (2013.01)

(58) **Field of Classification Search**

CPC B63G 8/08

USPC 114/332; 440/14, 15, 13

See application file for complete search history.

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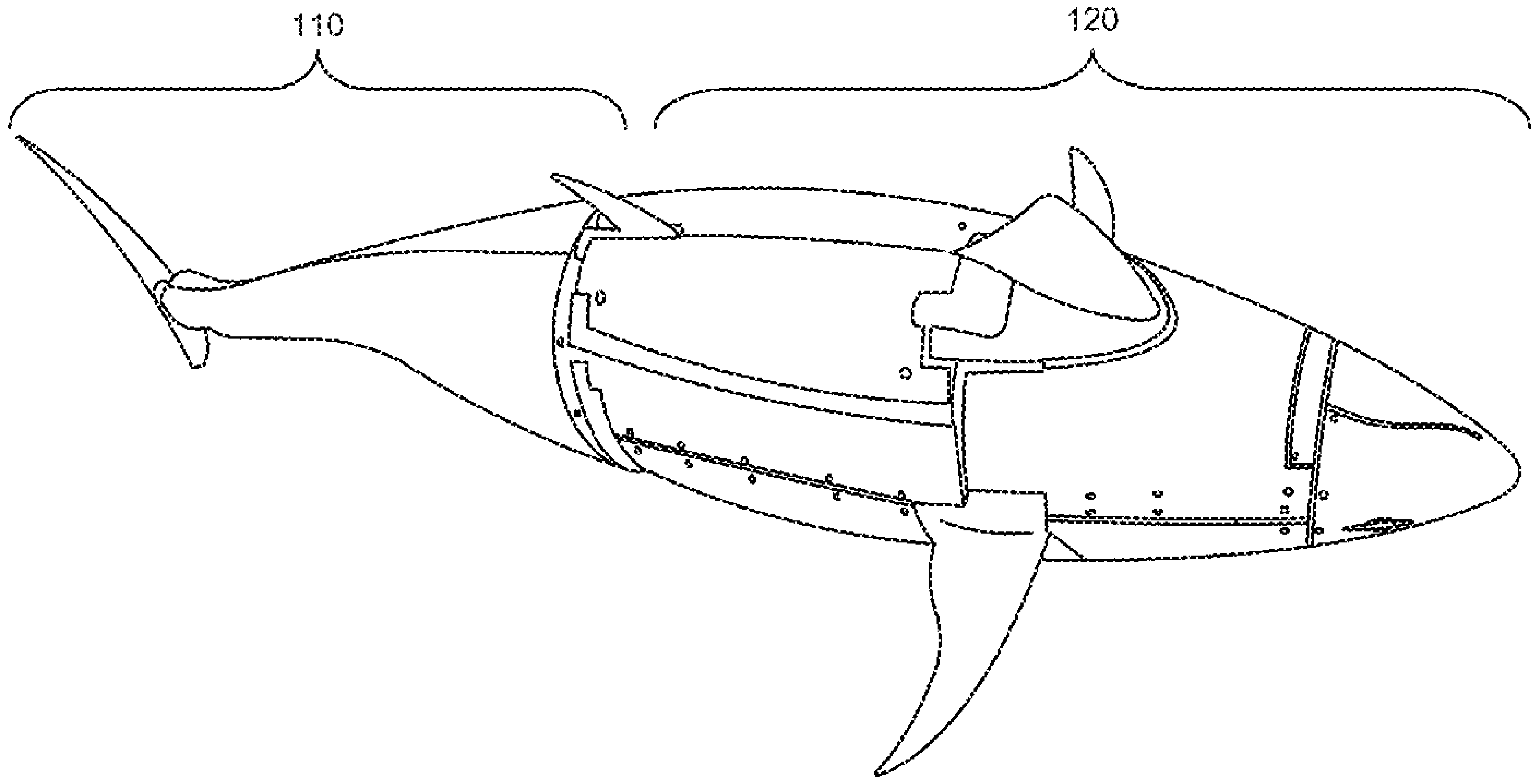
(57) **ABSTRACT**

An underwater vehicle includes a fore-body and a flexible aft. The flexible aft includes a flexible body. The flexible body includes a spring body including a spring element extending along a main axis, and a cavity. Related apparatus, systems, techniques, and articles are also described.

35 Claims, 23 Drawing Sheets



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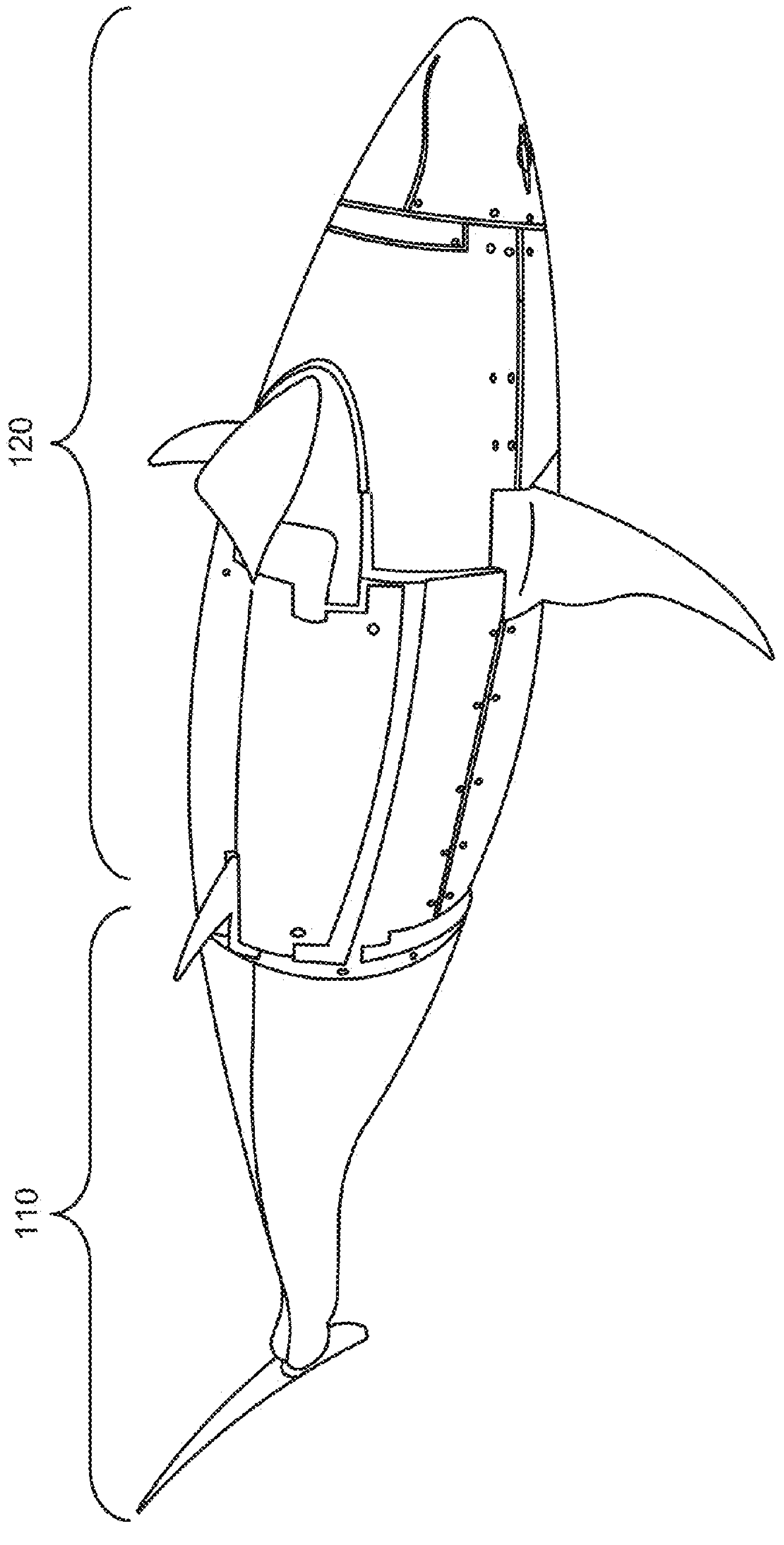

FIG. 1

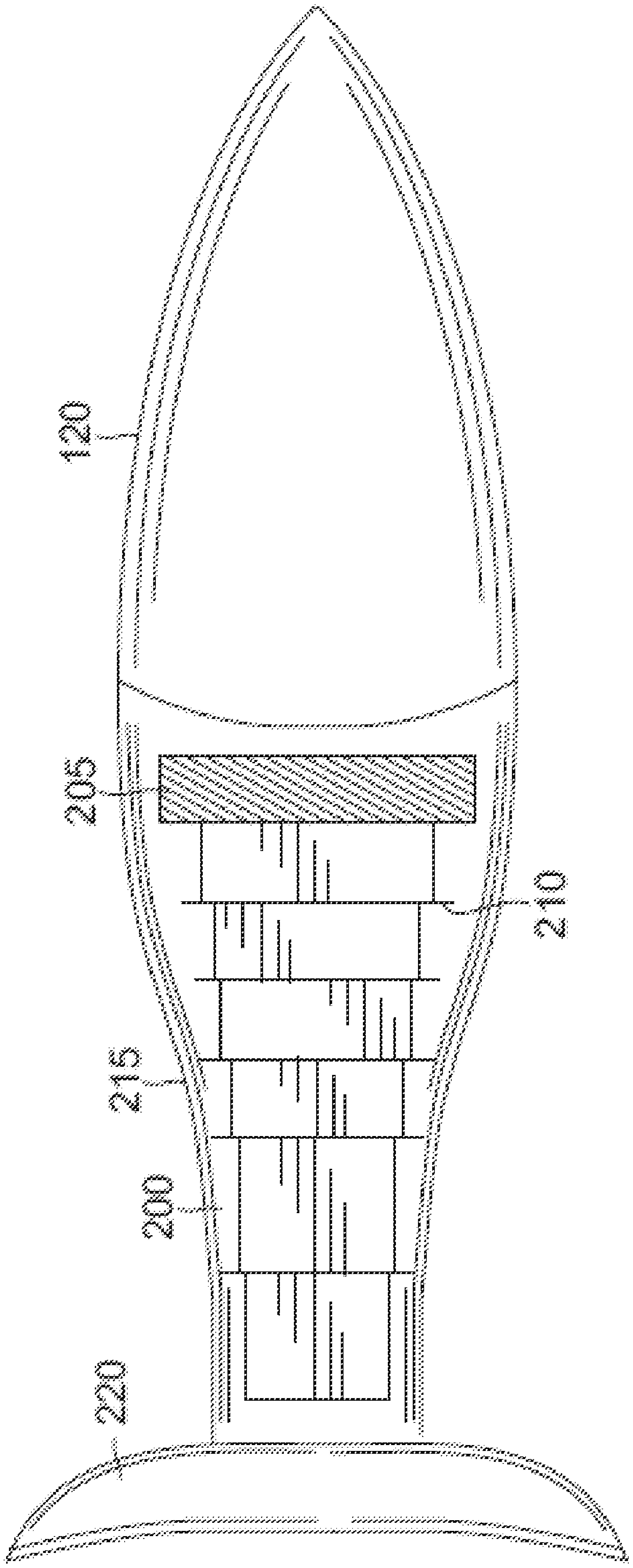

FIG. 2

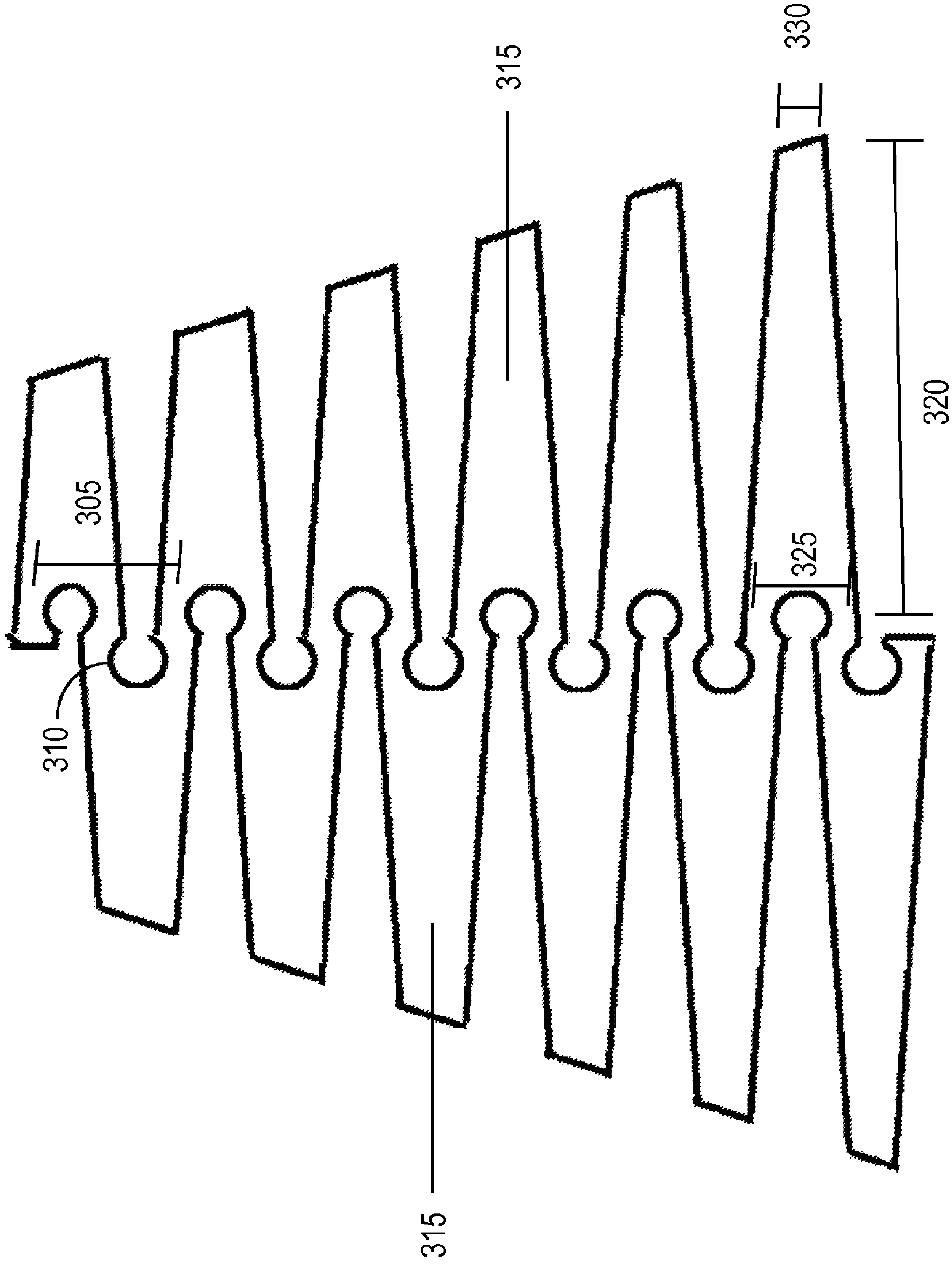

FIG. 3

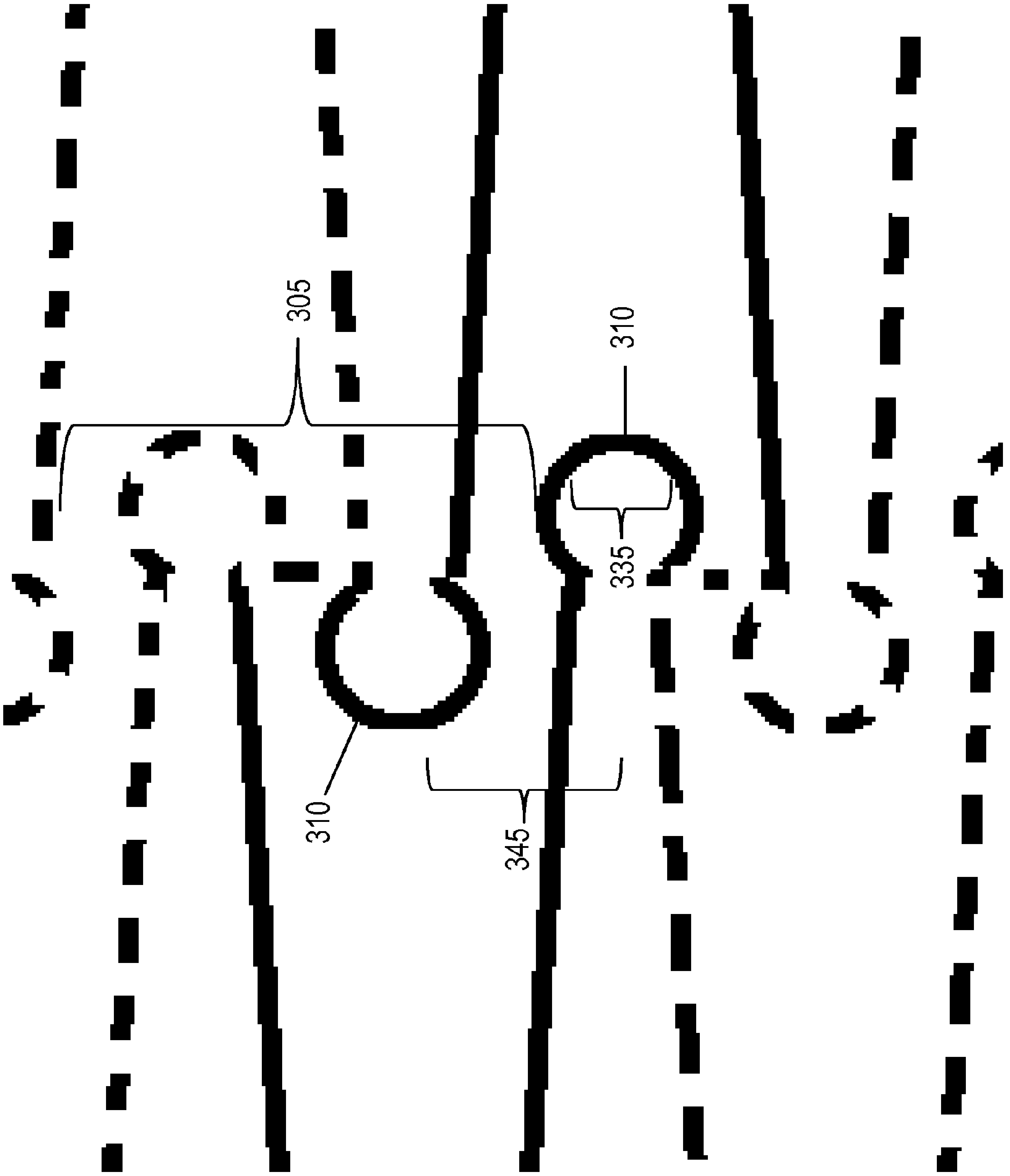

FIG. 4

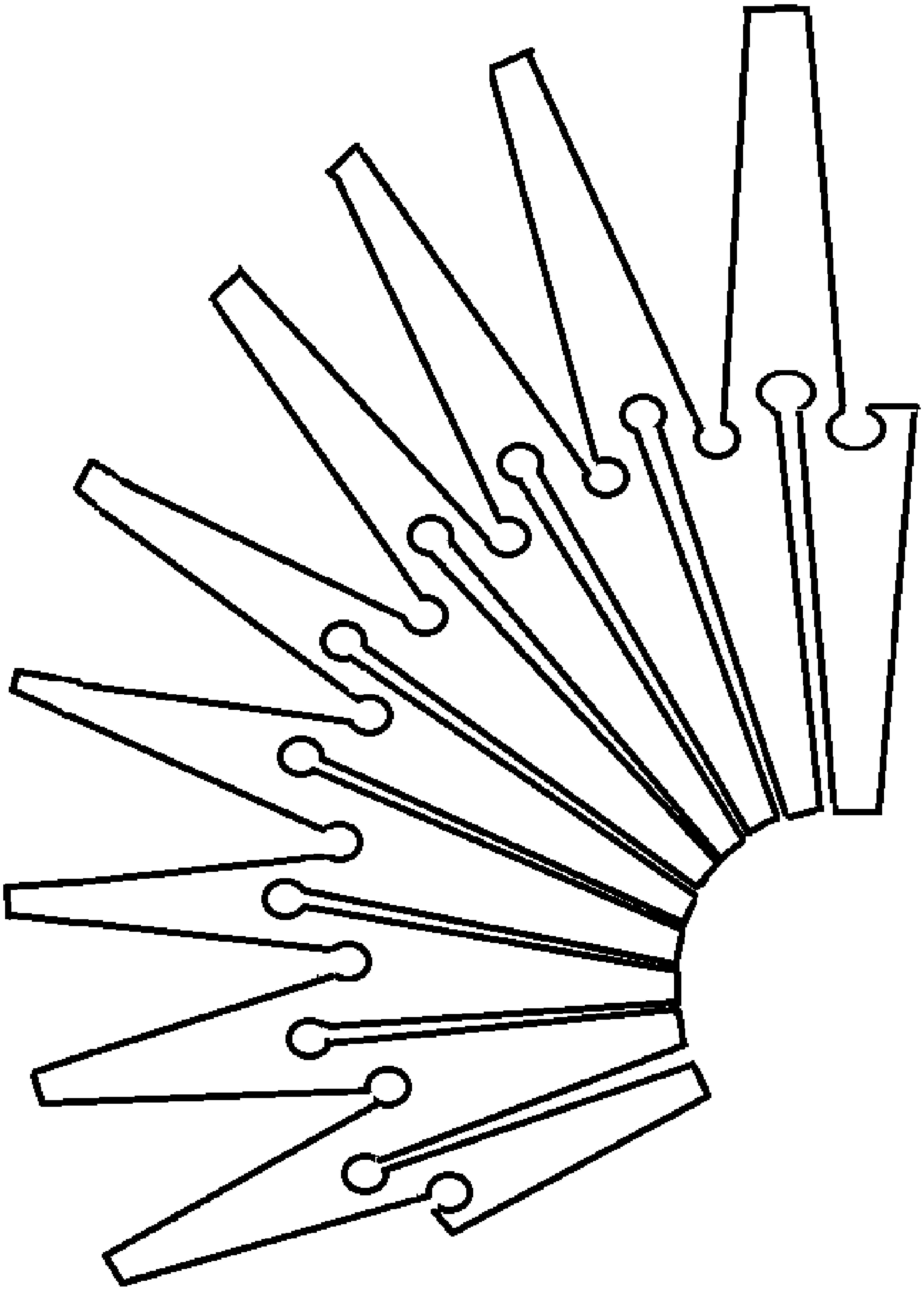

FIG. 5

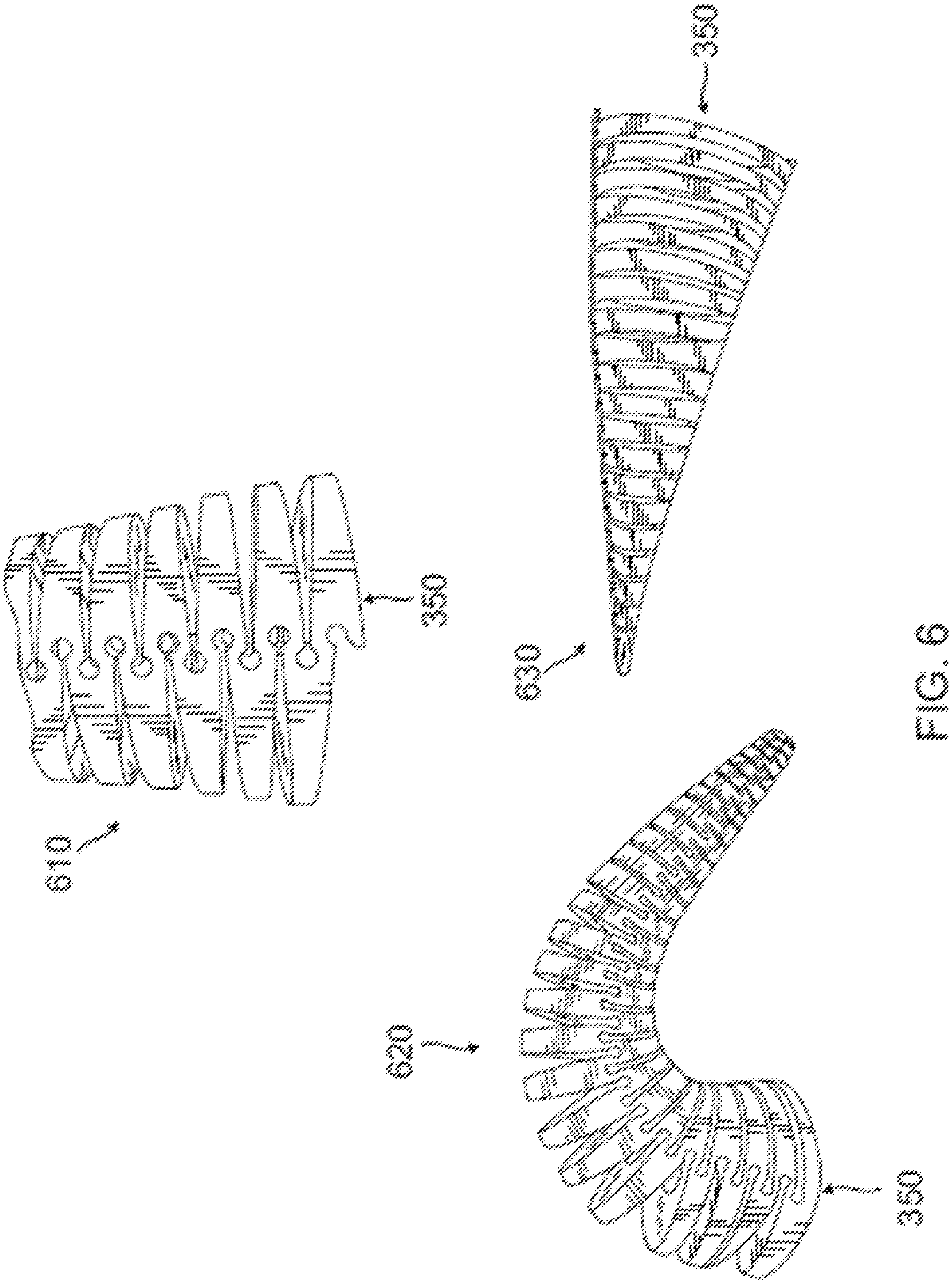

FIG. 6

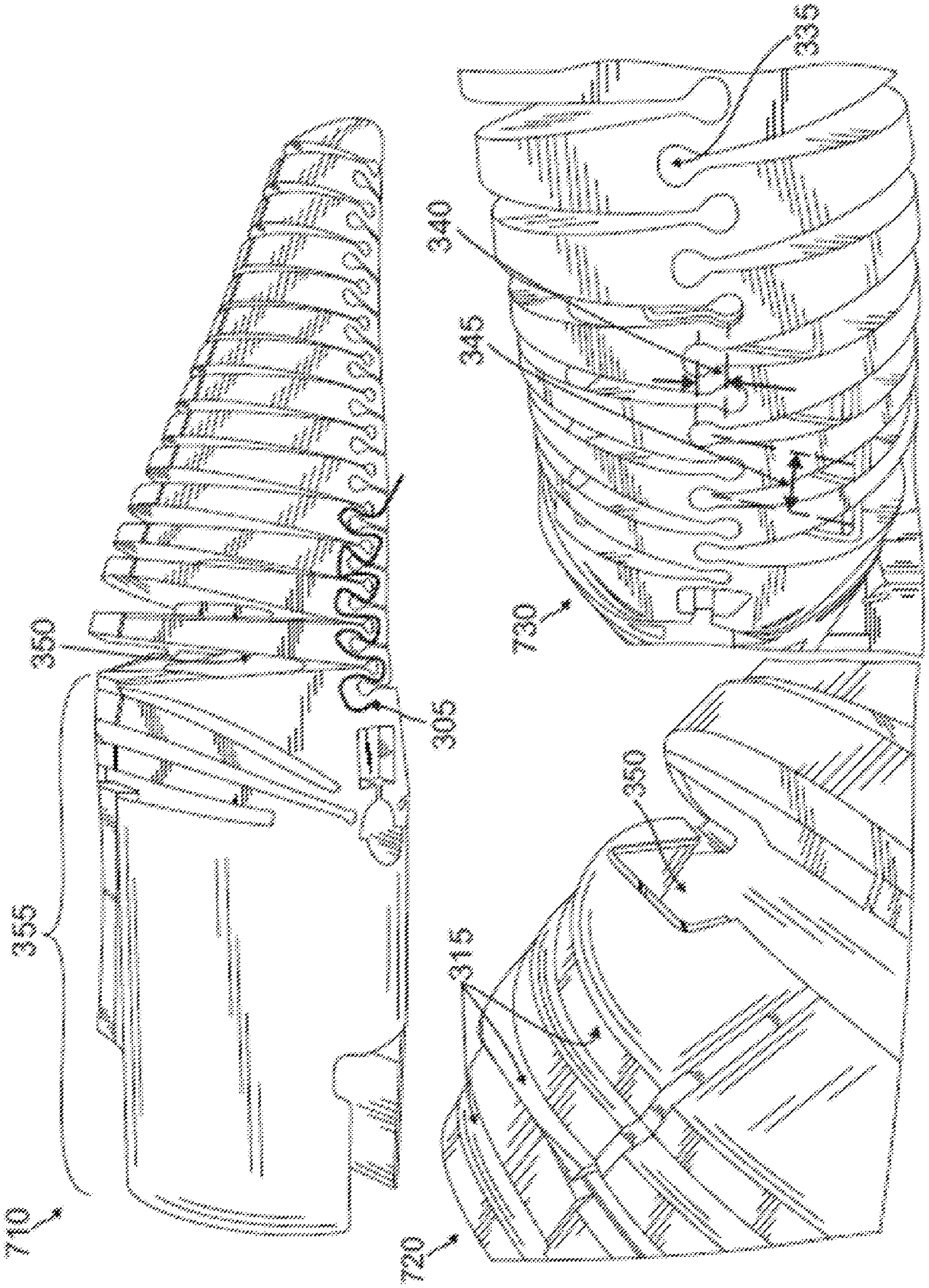

FIG. 7

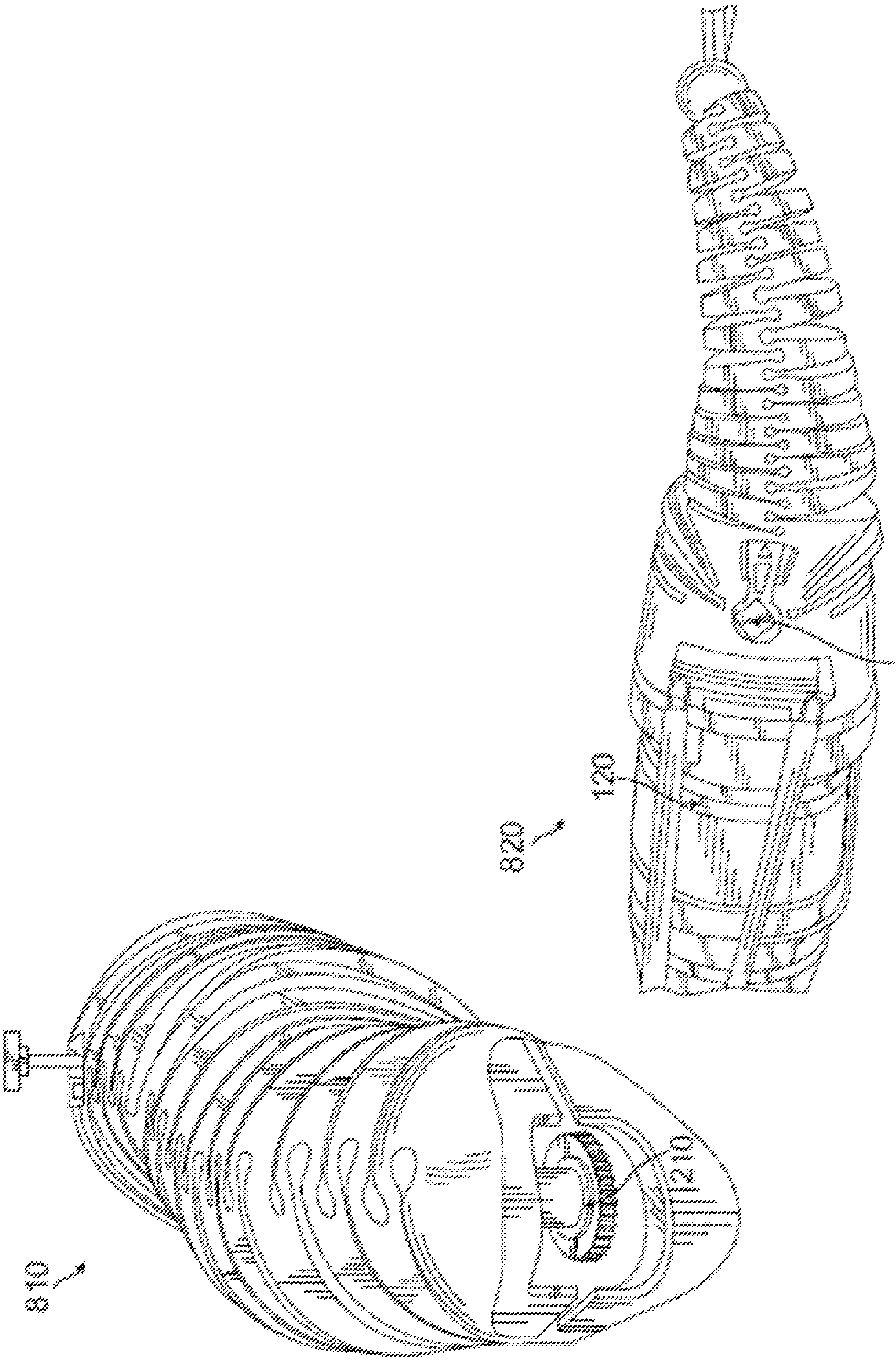

FIG. 8

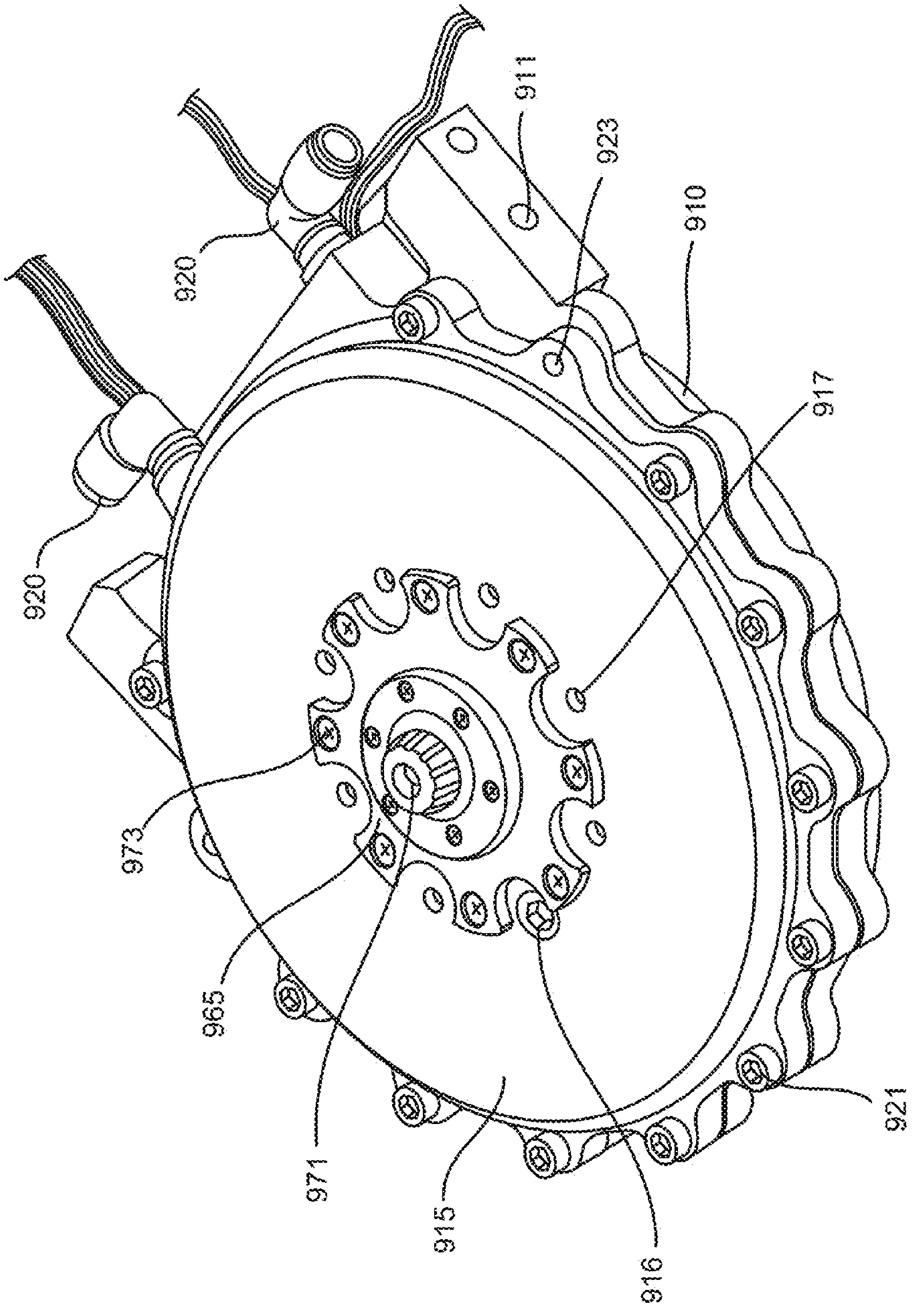

FIG. 9

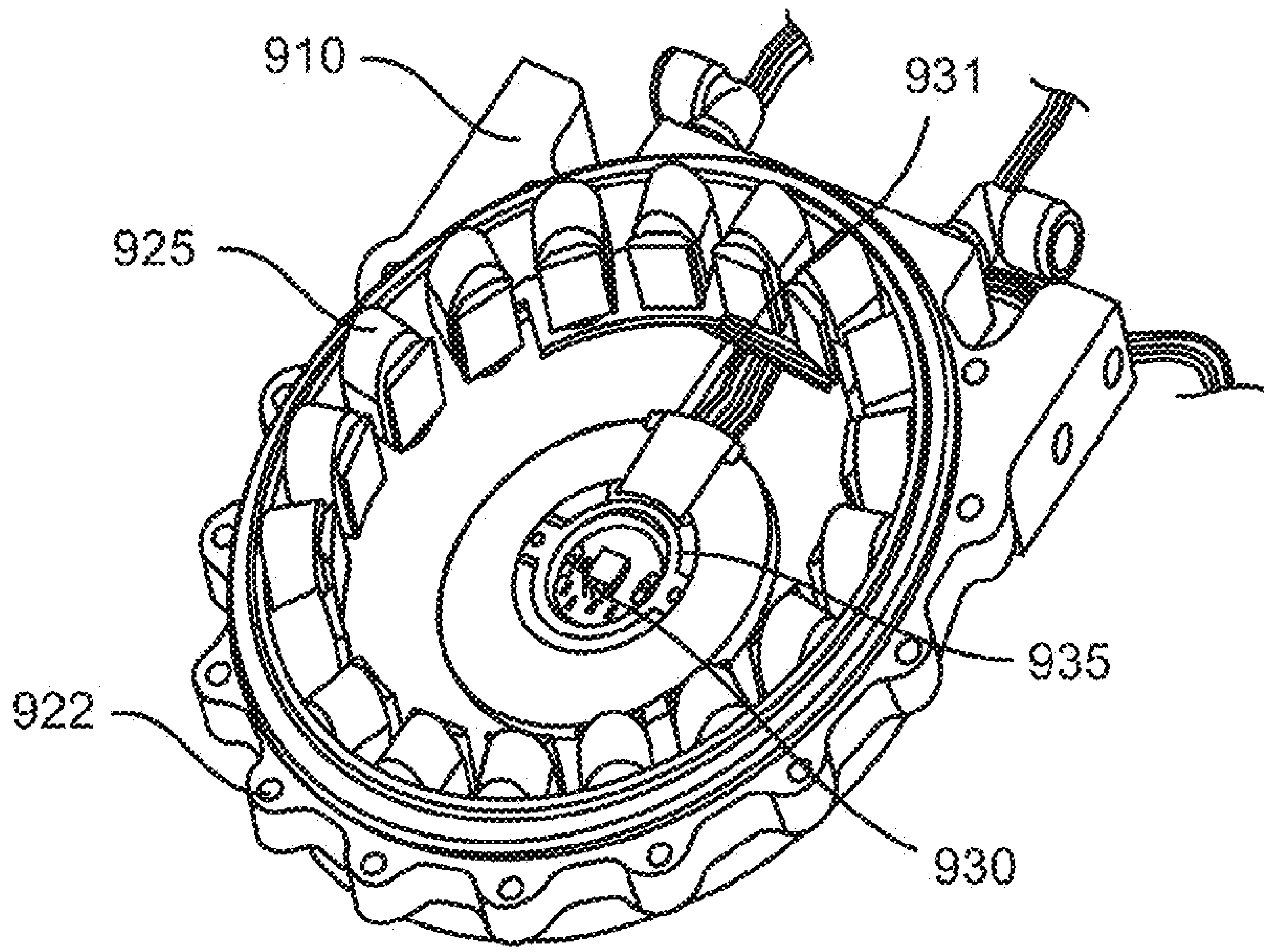

FIG. 10A

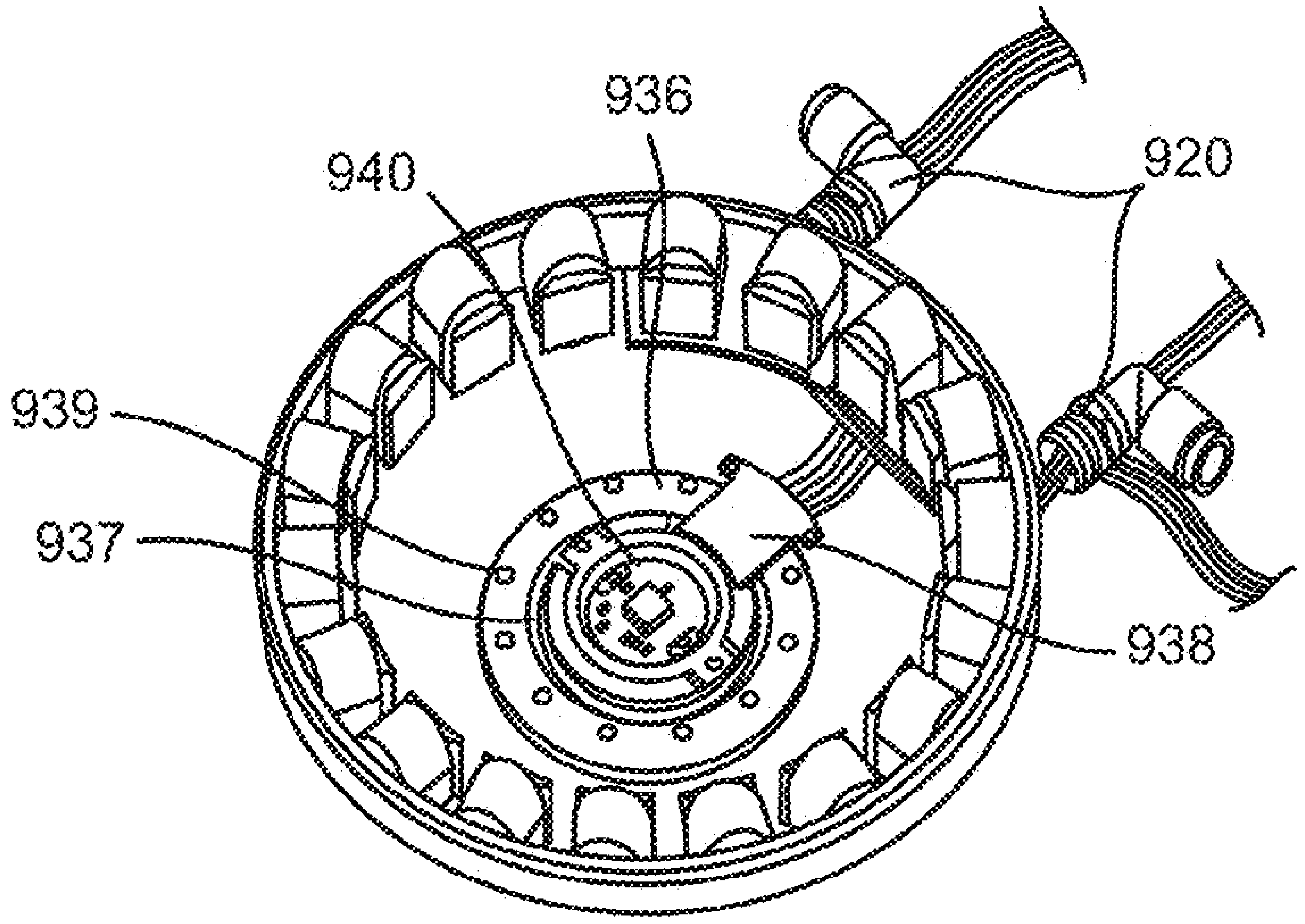

FIG. 10B

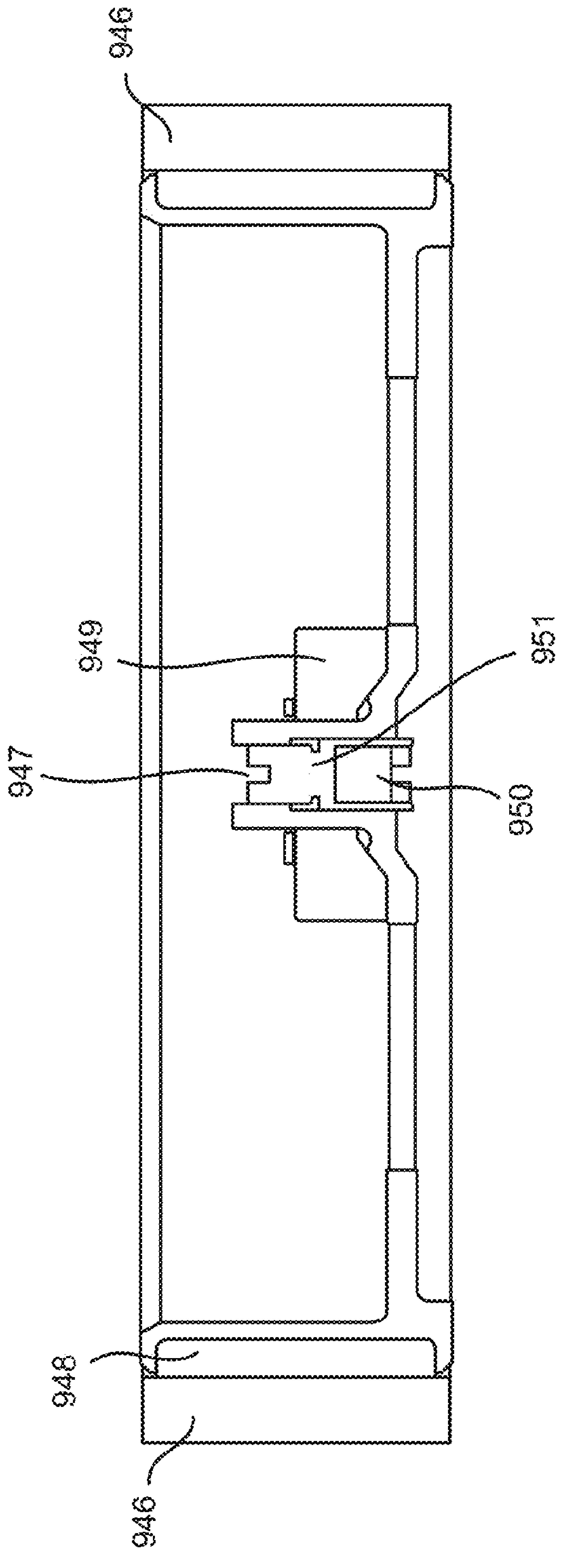

FIG. 11

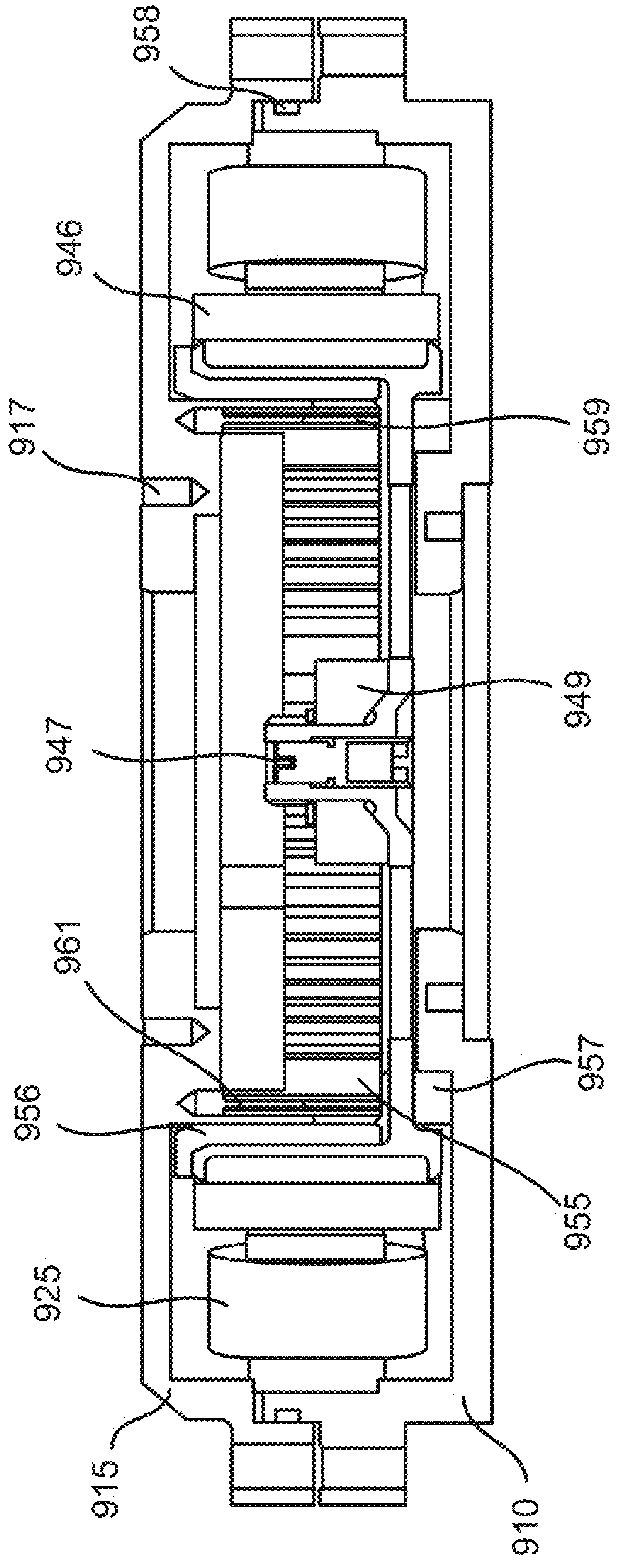

FIG. 12

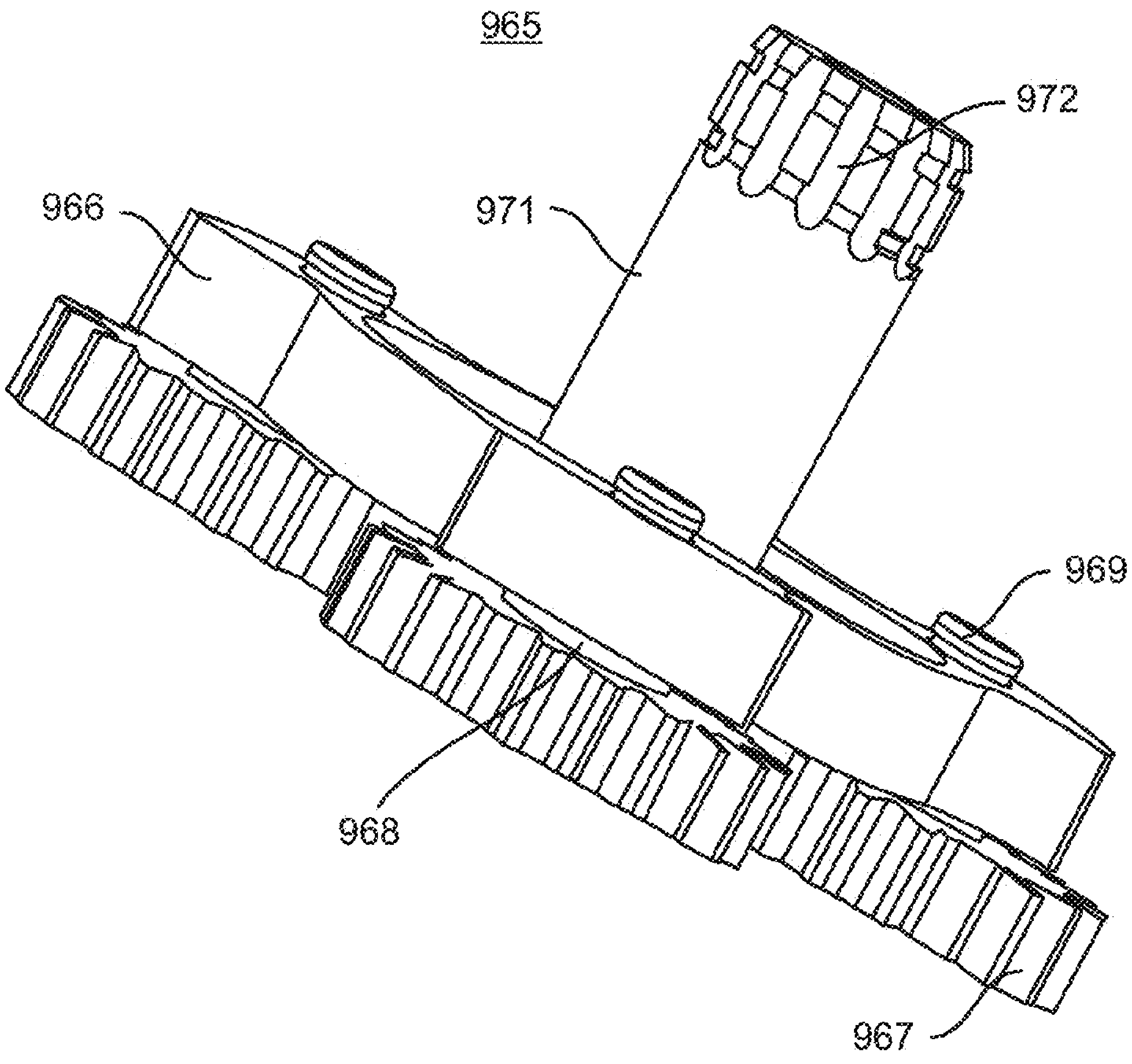

FIG. 13A

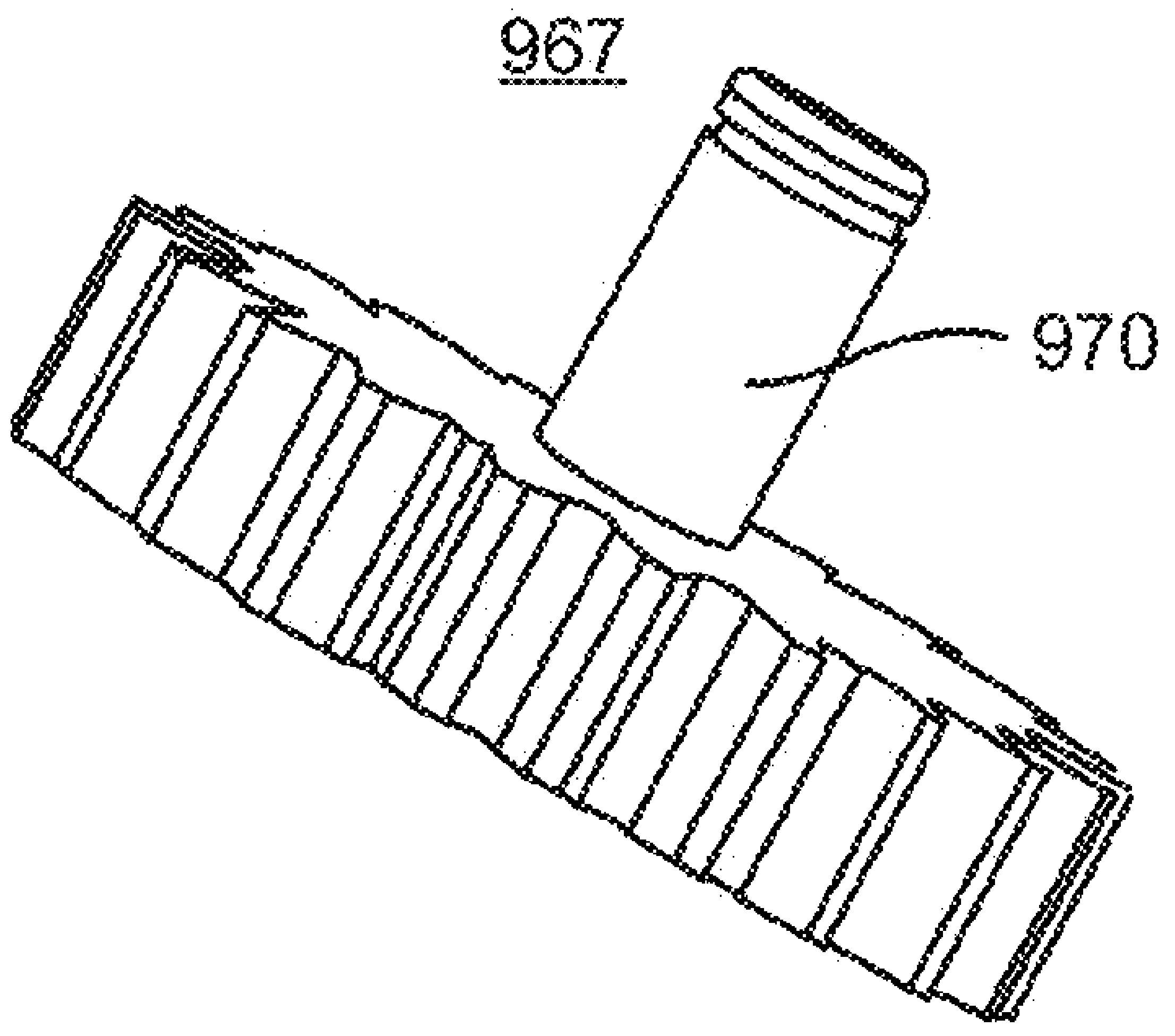

FIG. 13B

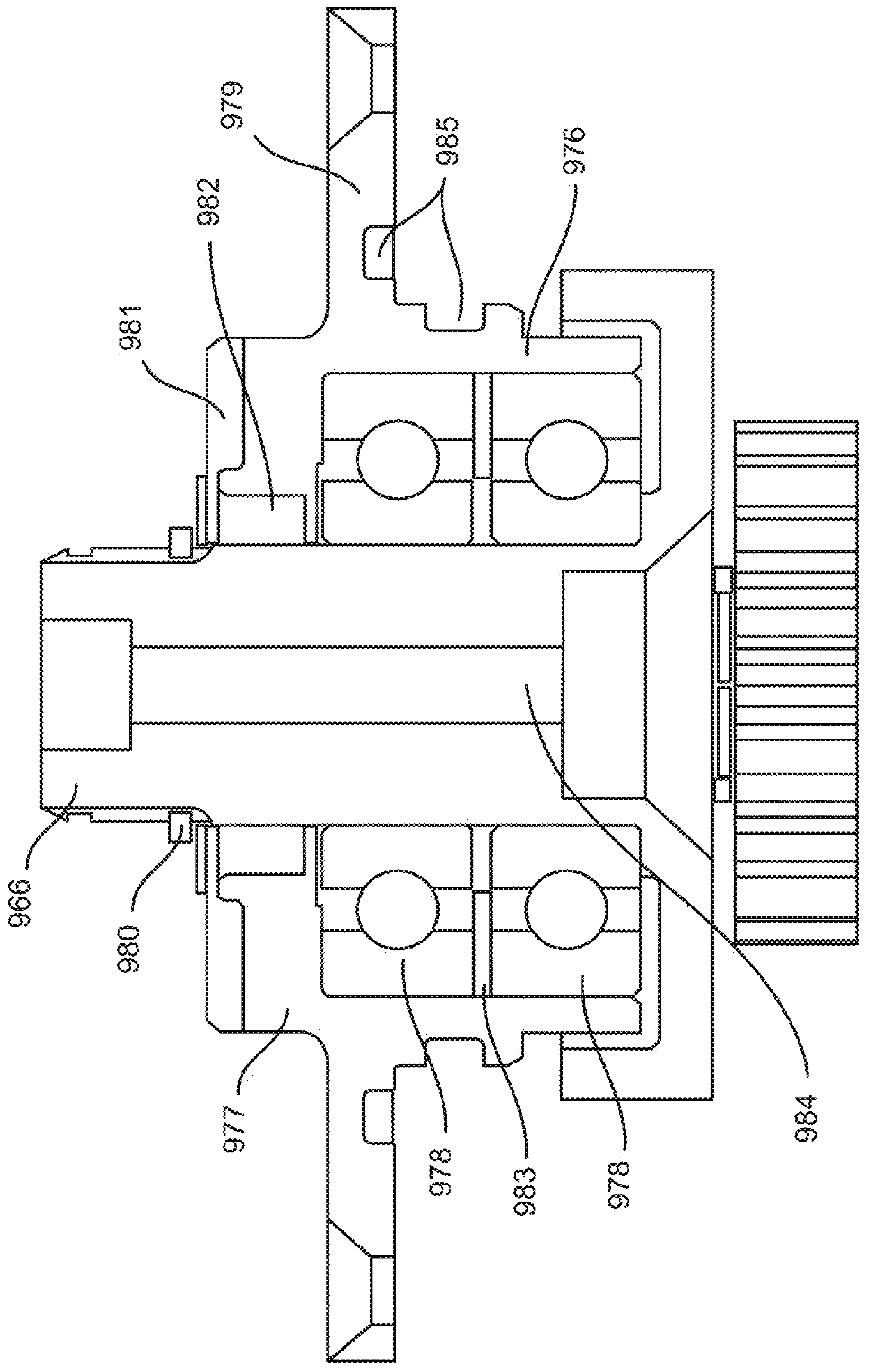

FIG. 14

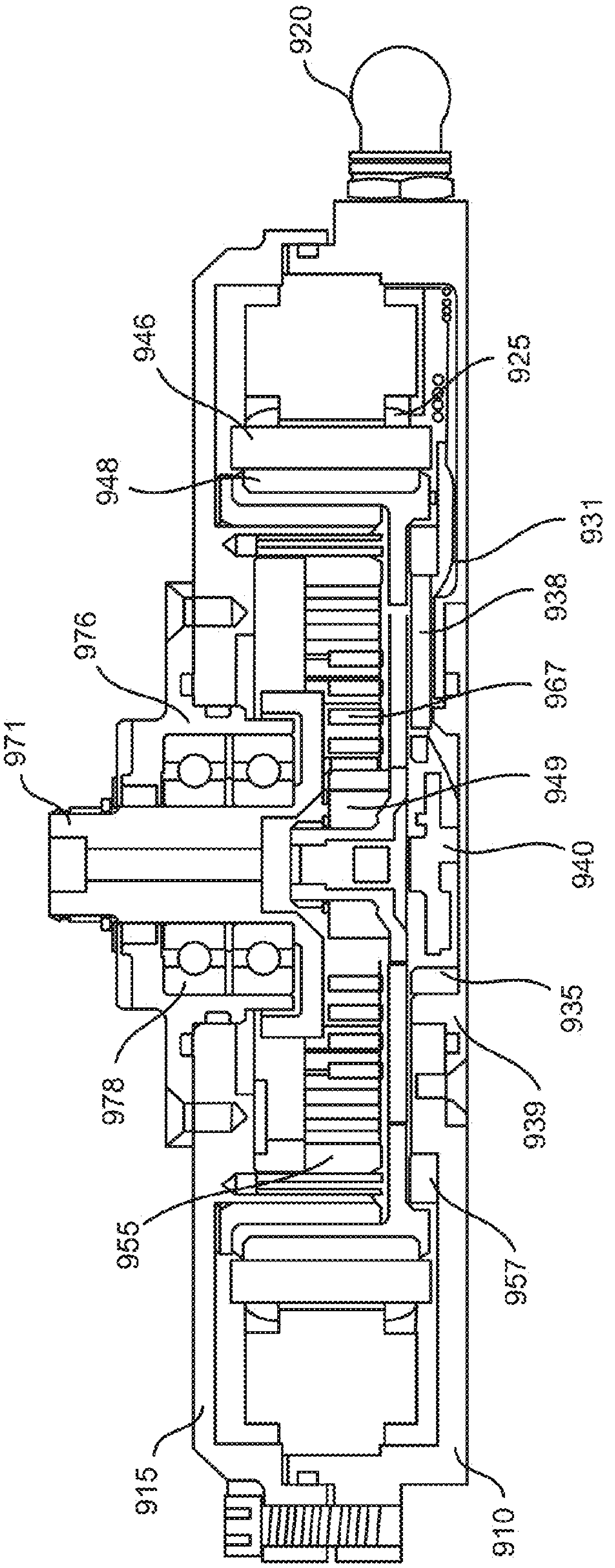
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FIG. 15

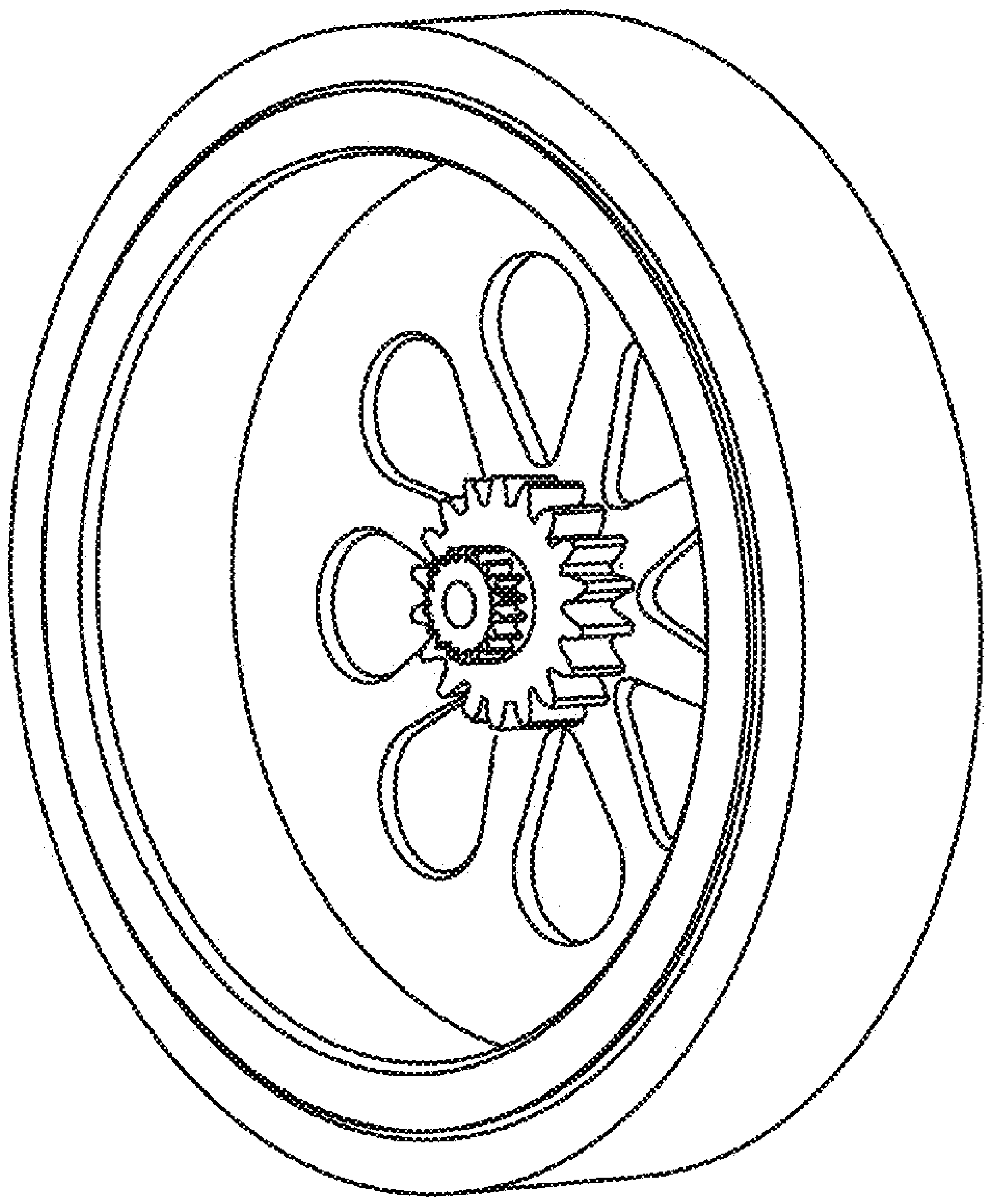


FIG. 16

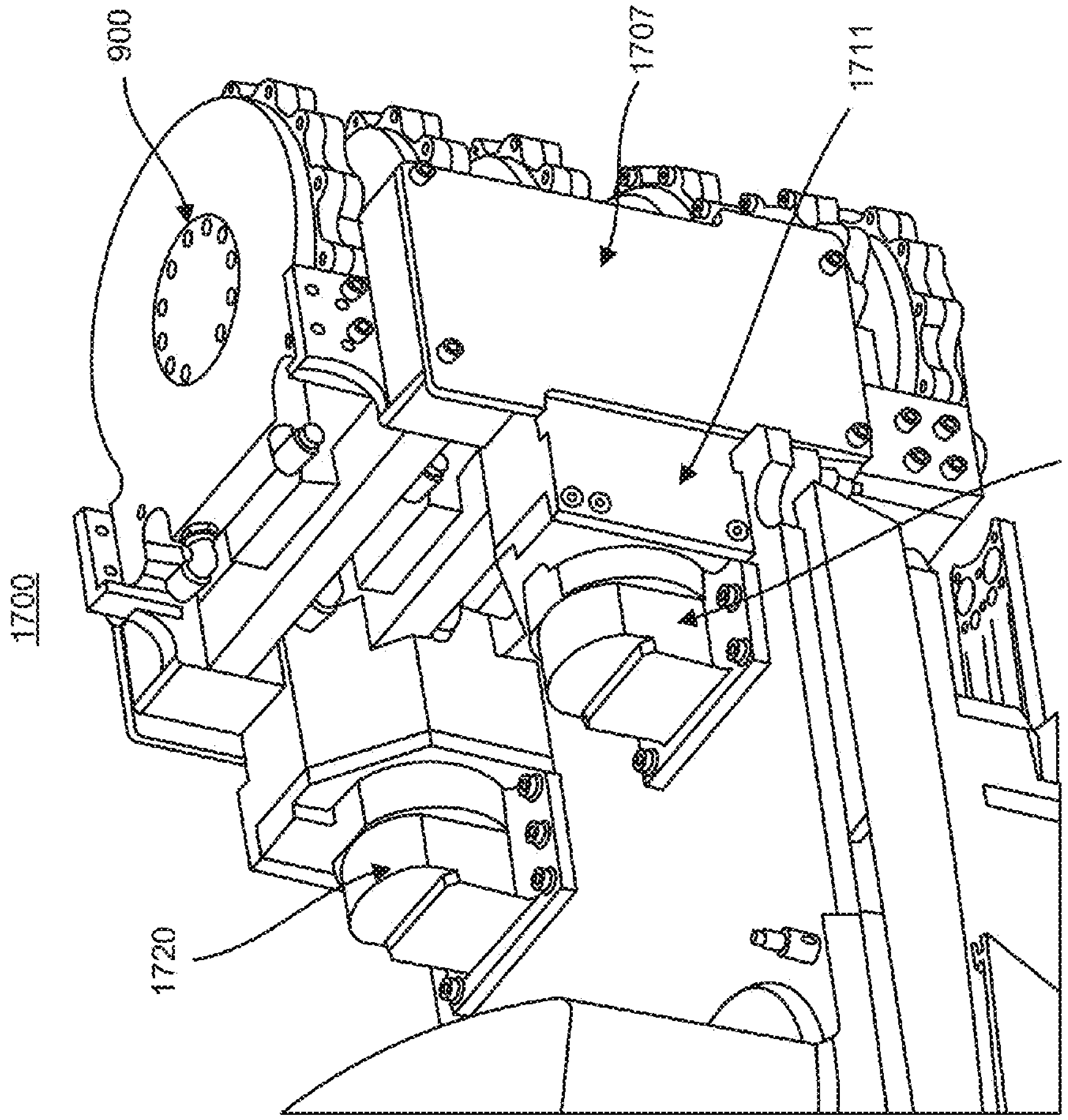


FIG. 17

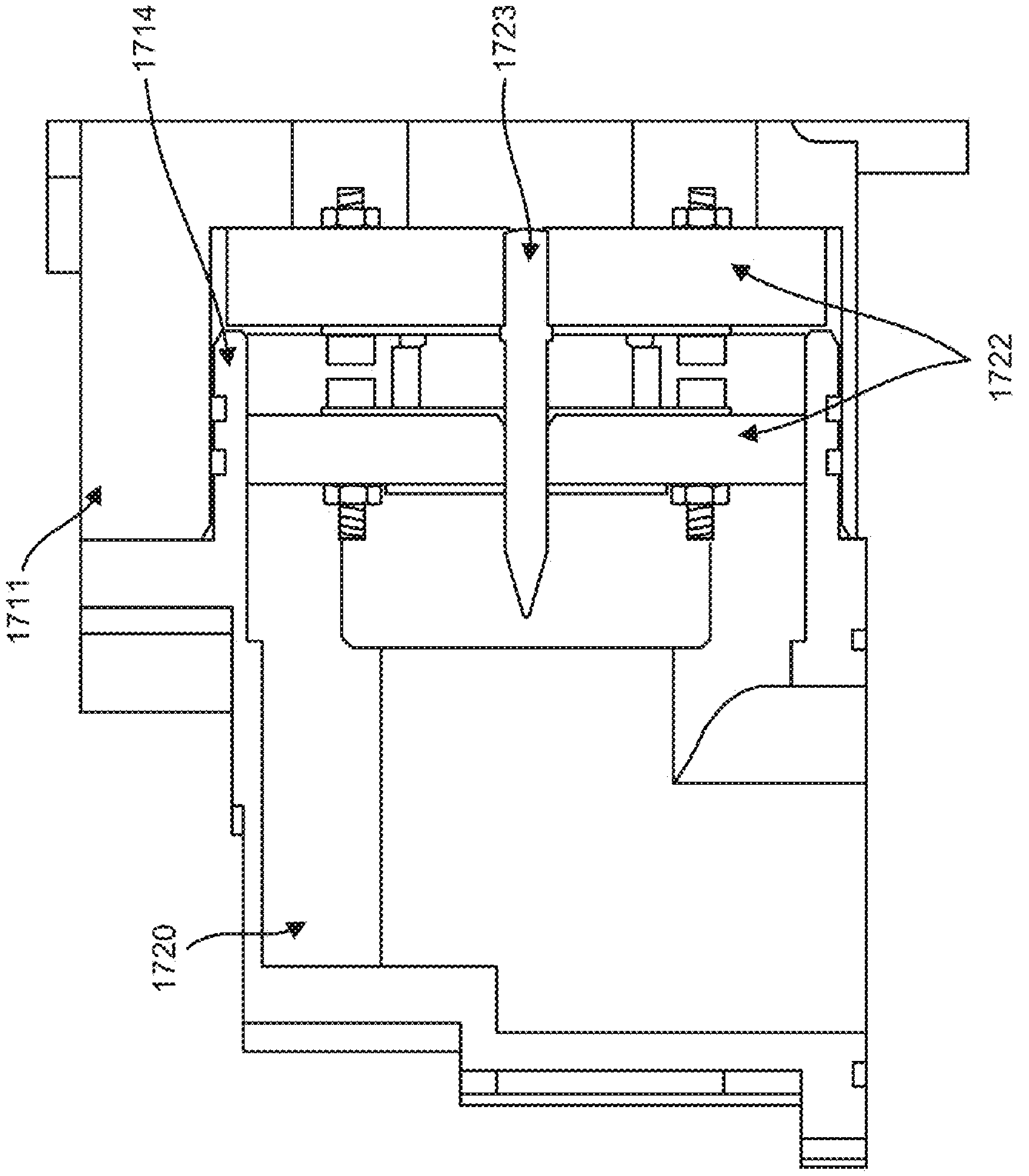


FIG. 18

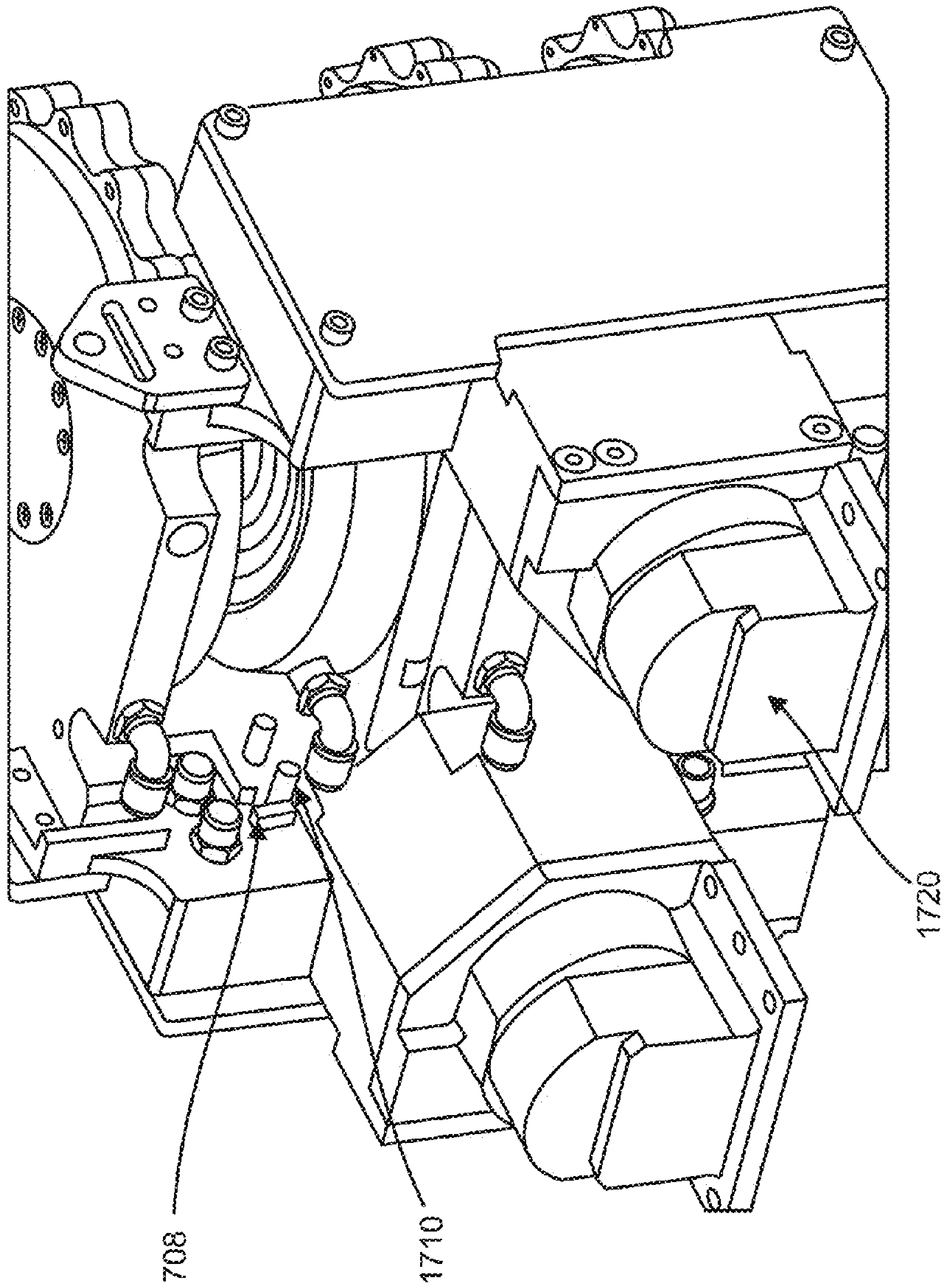


FIG. 19

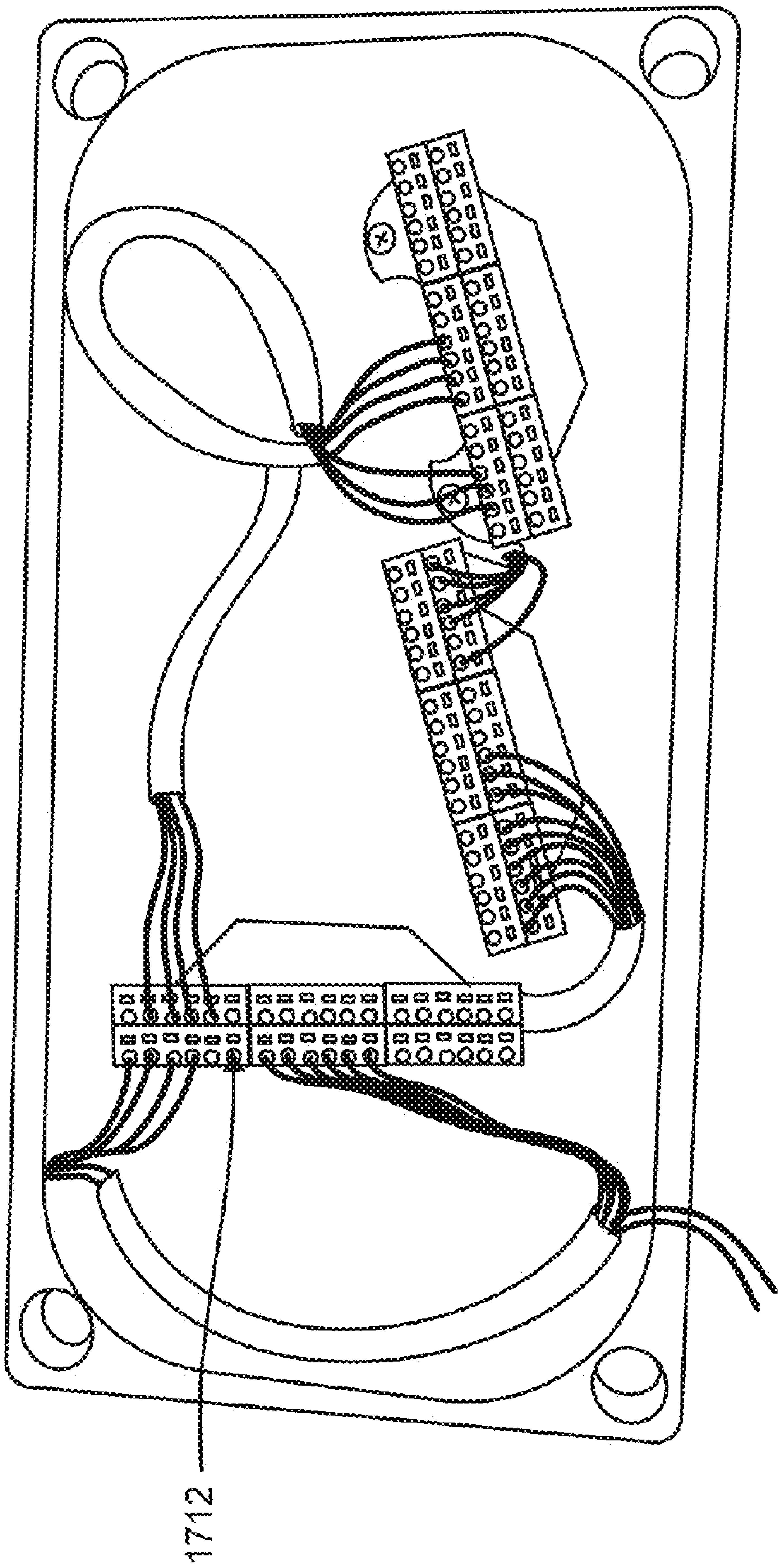


FIG. 20

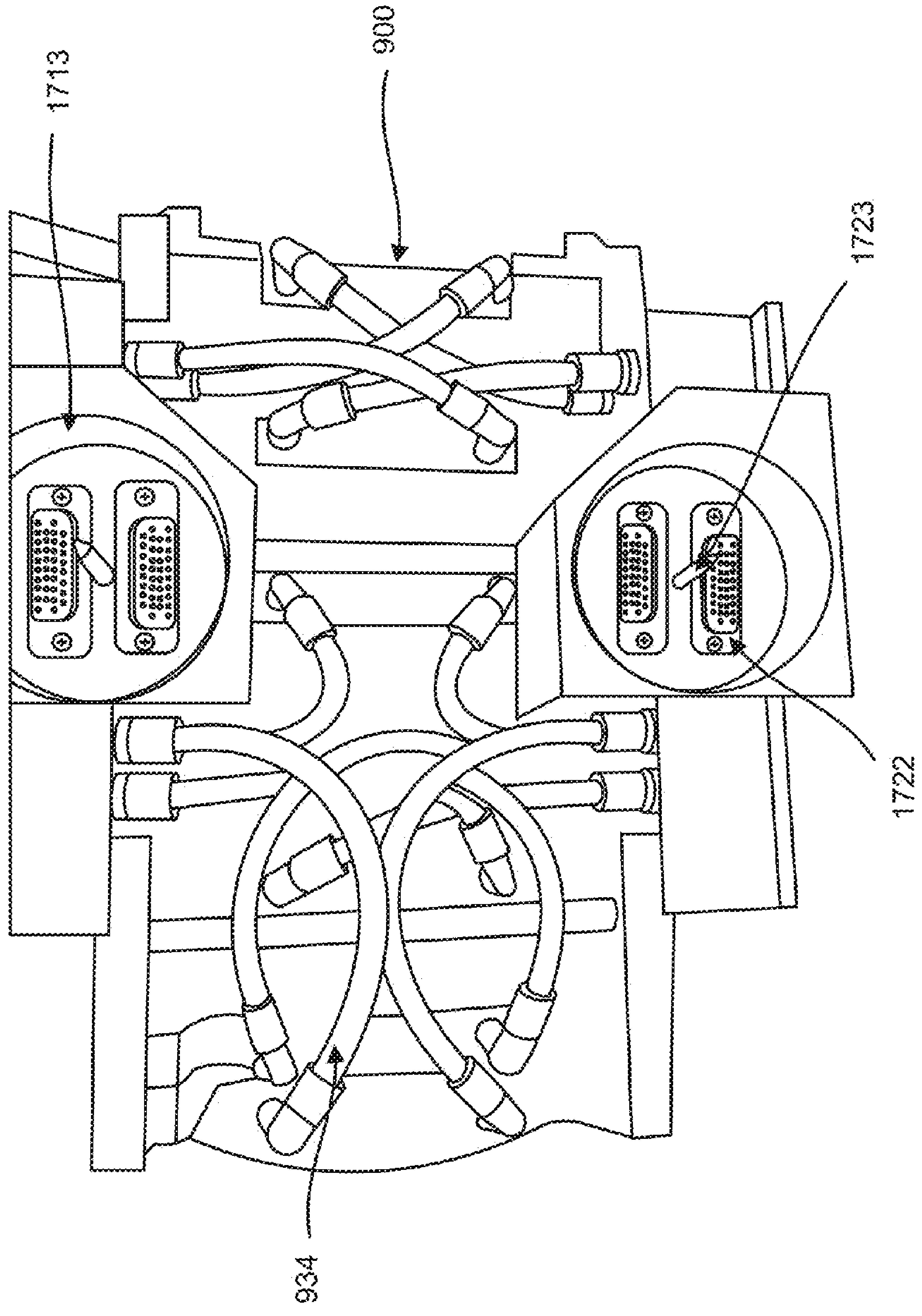
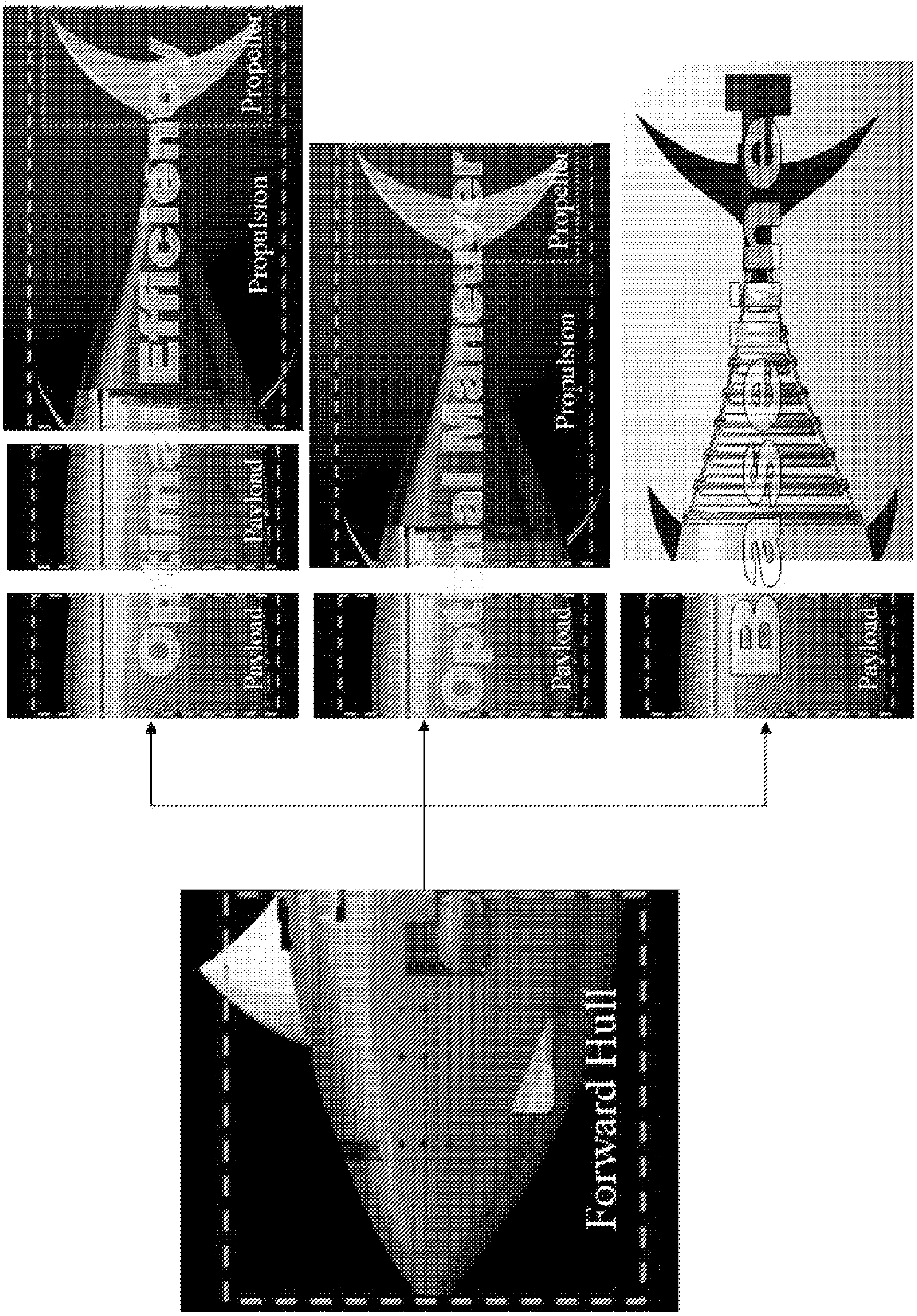


FIG. 21


Forward Hull
Payload
Payload
Propulsion
Propeller
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Propulsion
Propeller
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FIG. 22

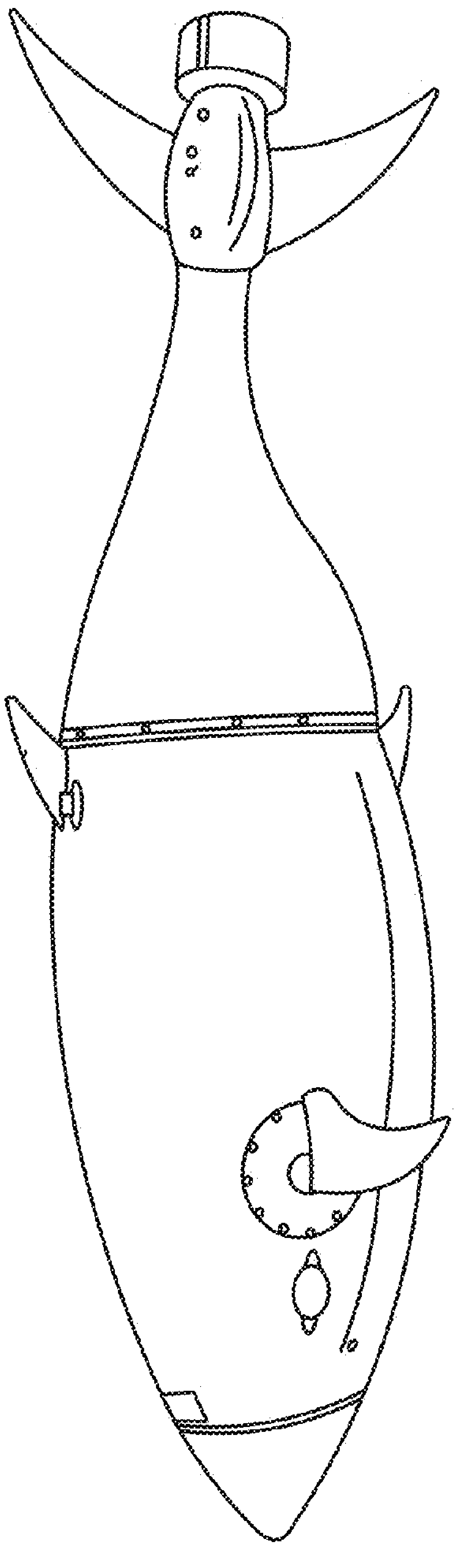

FIG. 23

AQUATIC VEHICLE

RELATED APPLICATIONS

This application claims priority to U.S. Provisional Application No. 61/716,236, filed Oct. 19, 2012, the entire contents of which is hereby incorporated by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

At least a portion of the current subject matter was made with government support under contracts numbered N00014-09-C-0657, N00014-08-M-0294, and SBIR N08-T030 awarded by the Department of Defense. The government may have certain rights in the invention.

TECHNICAL FIELD

The subject matter described herein relates to highly maneuverable underwater vehicles with efficient propulsion.

BACKGROUND

An autonomous underwater vehicle (AUV) is a robot that can operate in underwater and unstructured environments without continuous human guidance. AUVs constitute part of a larger group of undersea systems known as unmanned underwater vehicles (UUVs) (alternatively referred to as unmanned undersea vehicles), a classification that includes non-autonomous remotely operated underwater vehicles (ROVs)—controlled and powered from the surface by an operator/pilot via an umbilical or using remote control.

AUVs can rely on a number of propulsion techniques, but propeller based thrusters or Kort nozzles are the most common by far. These thrusters are usually powered by electric motors and sometimes rely on a bore or lip seals in order to protect the motor internals from electric shorting and corrosion. An alternative to propeller-based propulsion includes underwater gliding. An underwater glider is a type of AUV that do not directly propel themselves. They use small changes in buoyancy in conjunction with wings to convert vertical motion to horizontal, and thereby propel themself forward with a sawtooth-like up-and-down profile through the water. Because of their low speed and low power electronics, the energy required to cycle trim states is far less than for regular AUVs. In this manner, gliders trade speed and responsiveness for endurance and gain a significant increase in range and duration of operation compared to vehicles propelled by electric motor-driven propellers. However, no current AUV is capable of all aspects; speed, maneuverability, and endurance.

Existing UUVs are commonly cylindrical and exhibit poor maneuverability, particularly in littoral and riverine areas. They often use rigid bodies combined with propellers and as a result can be limited in efficiency (of propulsion and maneuvering) by the practical propeller diameter, exhibit poor transiency response, and low propulsion efficiency over ranges of speeds and maneuvers. A lack of control authority caused by a single propeller based system with a rigid body can prevent the execution of missions in cluttered and complex environments.

SUMMARY

An underwater vehicle includes a fore-body and a flexible aft. The flexible aft includes a flexible body, a drive system, and an actuator system.

In one aspect, a flexible body includes a spring body including a spring element extending along a main axis and a cavity within the spring body.

In another aspect, an aquatic vehicle includes a fore-body, an aft section, and an actuator system at least partially within the aft section. The aft section is configured such that, when the aquatic vehicle is within liquid, at least a portion the aft section is flooded with liquid such that at least a portion of the actuator system is submerged. The actuator system is configured such that, when the actuator system is operated while at least a portion of the actuator system is submersed in liquid, the liquid serves to transfer thermal energy produced by the actuator system away from the actuator system.

In yet another aspect, an aquatic vehicle includes a fore-body, an actuation system connected to the fore-body, a drive system comprising a plurality of flexure points and actuated by the actuation system, and a flexible body attached to the fore-body and enclosing at least a portion of the drive system. The flexible body includes a spring body, which includes a spring element extending along a main axis, and a cavity within the spring body.

One or more of the following features can be included. For example, the flexible body can include features extending in a second axis perpendicular to the main axis and defining an outer shape. The cavity can be within one or more of the features. Each spring element can include two opposed semicircular portions formed in an S shape and the features extending in the second axis can include tabs. Each feature can be integral with a corresponding semicircular portion such that each spring element has at least two opposite facing features. The flexible body outer shape can be biomimetic, conic, or cylindrical. The features can taper along the main axis.

The spring body can include a plurality of spring elements. One or more attributes of the spring elements can vary among the spring elements. The attributes can include one or more of shape, amplitude, frequency, materials, and thickness. The attributes can vary such that when deflected, the flexible body moves in a biomimetic motion. The cavity can extend the entire length of the spring body. The cavity can extend through a partial length of the spring body. The cavity can include a plurality of discreet cavities. At least a portion of a drive system can reside within the cavity. The flexible body can form a frame structure for a drive system contained at least partially within the cavity. The flexible body can be attached to a fore-body. Each spring element or their combination can be biomimetic.

The aquatic vehicle actuator system can include a top housing, a bottom housing affixed to the top housing, a rotor assembly, a mechanical reduction assembly, and a bearing housing. The bottom housing can include a main body, a feedback sensor, a stator, and a thrust bushing. The rotor assembly can be disposed within the bottom housing and top housing and can include a rotor, a rotor hub, and a rotation element. The mechanical reduction assembly can be disposed within the bottom housing and top housing, and can be coupled to the rotor assembly rotation element. The mechanical reduction assembly can include a mechanical reduction, one or more rotation elements, and an output shaft. The bearing housing assembly can be affixed to one of the top housing and bottom housing and can provide for a rotation of the mechanical reduction. The bearing housing assembly can include a bearing, and a bearing housing.

An electrical current applied to the stator can cause the rotor assembly to rotate around the rotor hub, thereby causing the mechanical reduction output shaft to rotate. The rotor assembly rotational element can be coupled to the one or more mechanical reduction rotational elements such that a rotation of the rotor imparts a rotation to the mechanical reduction. The actuator system can include ports and features to enable seal testing.

When the aquatic vehicle is submerged in liquid, the aft can allow liquid to move between an interior and exterior of the aft, the exterior of the aft including an external environment. The aft can comprise a flexible body. An outer shape of the vehicle can be biomimetic, conical, or cylindrical. The vehicle can be configured for biomimetic propulsion.

The actuation system can include an actuator, one or more interface supports having features, electrical connections, a seal, and the actuator being secured to the features, and one or more connector blocks connected to the fore-body and the interface supports. The actuation system can disconnect from the fore-body. A second different actuation system can connect to the fore-body.

The drive system can include a body with one or more flexible points in the body, first connectors coupled to the actuation system at a first end, and second connectors coupled to a propulsive element at a second end. The aquatic vehicle can include a propulsive element located at a posterior end of the vehicle. The propulsive element can include one or more of: foil, biomimetic foil, thruster, and water jet.

The flexible body can define a volume, and when the aquatic vehicle is submerged in liquid, a portion of the volume can be flooded with the liquid such that, at least a portion of one or more of the actuation system and the drive system can be submerged.

The subject matter described herein provides many advantages. For example, the current subject matter provides improved maneuverability (e.g., small turning radius), higher maneuverability efficiency (e.g., maneuvers require less energy), higher propulsion efficiency (at both low and high speeds), and higher operating speeds (both straight line and during maneuver) when compared to prior UUVs. The greater energy efficiency enables longer operation times, unattended mission execution, increased operation range, improved payload capacity (as a percentage of total vehicle volume and/or weight).

Additionally, the current subject matter can operate in environments with confined spaces, exhibiting increased flow and unsteady water conditions, as well as environments that require frequent maneuvering (e.g., winding scenarios). Prior UUVs require considerable energy to make planar turns due to their large turning radius while the current subject matter achieves the same maneuver in a shorter time span and with minimal impact to normal operating energy usage.

An actuation system can provide operation in a submerged state. The actuation system removes the requirement for seals, sealing features, sealing housings, and other like items. This enables improved performance, improved reliability, and reduced cost. Performance is improved by the elimination of drag losses and adverse dynamic damping effects from seals, and provides infinite and omnidirectional heat sinking to the environment such that thermal power losses are reduced and the actuator can be driven at peak power levels (including, in some implementations, above power levels specified by manufacturers). Cost is reduced through minimizing part count, eliminating requirements for scheduled maintenance, and minimization of assembly steps in production. Reliability is increased through the removal of risk of overheating of electrical components, removal of potential failure points in the system, and removal of the requirement for regular maintenance.

Submersion of an actuator can apply to various technologies. For example, electromechanical actuators, Lorentz actuators, shape memory alloys, and artificial muscles.

The current subject matter can be applied in the oil and gas industry for exploration, mapping, and surveillance for natural energy sourcing and pipeline operations. Additionally, the current subject matter's high maneuverability and rapid response at relevant speeds enables the current subject matter to operate in complex environments with many obstacles and unsteady fluid flows that less maneuverable UUVs cannot access. For example, the current subject matter can operate to inspect large-vessel propellers, operate between pier pilings, perform rescue missions up river, and environmental sensing in littorals (including near-surf zones). Embodiments of the current subject matter can be implemented to be man-portable and deployable from small crafts such as rigid-hulled inflatable boats.

The details of one or more variations of the subject matter described herein are set forth in the accompanying drawings and the description below. Other features and advantages of the subject matter described herein will be apparent from the description and drawings, and from the claims.

DESCRIPTION OF DRAWINGS

FIG. **1** is a photograph of an implementation of a UUV with a flexible aft and fore-body;

FIG. **2** is a drawing illustrating the components of an implementation of the flexible aft;

FIG. **3** is a drawing illustrating a cross section of an implementation of a flexible body;

FIG. **4** is a drawing illustrating a close up view of a cross section of an implementation of a spring element;

FIG. **5** is a drawing illustrating a cross section of an implementation of flexible body during deflection;

FIG. **6** is a series of drawings illustrating a cross section of an implementation of flexible body;

FIG. **7** is a series of drawings illustrating an example embodiment of the flexible body;

FIG. **8** is a series of drawings illustrating an example embodiment of the flexible body mounted to a fore-body, including an actuation system and a drive system;

FIG. **9** is a schematic illustrating an example embodiment of a fully assembled actuator;

FIG. **10**A is a schematic illustrating an embodiment of the actuator bottom housing assembly;

FIG. **10**B is the schematic of FIG. **10**A with a portion of the bottom housing assembly shown as transparent for illustrative purpose;

FIG. **11** is a schematic illustrating a cutaway perspective of an embodiment of the rotor assembly;

FIG. **12** is a schematic illustrating a cross section of an example embodiment of the actuator (shown without a mechanical reduction);

FIG. **13**A is a schematic illustrating an implementation of a mechanical reduction assembly;

FIG. **13**B is a schematic illustrating an implementation of planet gears;

FIG. **14** is a schematic illustrating an implementation of an assembled mechanical reduction and bearing housing assembly;

FIG. **15** is a schematic illustrating a cross section of an implementation of a fully assembled actuator;

FIG. **16** is a schematic illustrating a perspective of an embodiment of the rotor assembly;

FIG. **17** is a schematic illustrating an implementation of a stack of actuators in a support stack;

FIG. **18** is a schematic illustrating a cutaway perspective of an implementation of a connector block;

FIG. **19** is a schematic illustrating a close up perspective of an example actuator stack including interface support and connector blocks;

FIG. **20** is a photograph illustrating an example implementation of internal electrical connections, in this case terminal blocks;

FIG. **21** is a photograph of an example embodiment illustrating a rear perspective of the actuator stack;

FIG. **22** is a diagram illustrating some advantages of a modular UUV in accordance with the current subject matter; and

FIG. **23** is a photograph illustrating an alternative flexible aft embodiment wherein the propulsive element includes a foil and a thruster.

Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

FIG. **1** is a photograph of a biomimetic UUV with a fore-body **120** and a flexible-aft **110** or tail. Although, in the embodiment shown, the UUV is fish-shaped, other shapes are anticipated. For example, the fore-body **120** and/or flexible-aft **110** can be a simple tube or cylindrical shape and are preferably hydrodynamic (i.e., streamlined). To achieve propulsion, the UUV moves a propulsive element (such as a foil) attached to the end of the flexible aft **110** in a side-to-side (while side-to-side is used herein it is not intended to be limiting, for example, motion can be up-and-down/back-and-forth, etc.) direction thereby "swimming" in a manner similar to a fish. Biomimetic refers to human-made processes, substances, devices, systems, and the like, that imitate nature.

FIG. **2** is a drawing illustrating the components of the flexible aft **110**. The flexible aft **110** includes a flexible body **200**, an actuation system **205**, a drive system **210**, an outer skin **215**, and a propulsive element **220**.The flexible body **200** gives shape to the flexible aft **110**, covers the drive system **210**, and is flexible to allow for deflection by the drive system **210**. Additionally, the flexible body **200** is elastic (i.e., has spring characteristics) that can be utilized advantageously to improve propulsion and maneuvering efficiency. The propulsive element **220** can include a foil, thrusters, water jets, other propulsive means, or combinations thereof.

FIG. **3** is a drawing illustrating a cross section of an implementation of a flexible body **200**. The flexible body **200** is a spring body that includes one or more spring elements **305**. In this implementation, the elements are S-shaped spring elements **305** and are formed end-to-end along a main axis. Each spring element **305** can include two opposed open elements **310** (e.g., semicircular or semi-annular elements). For each open element, a feature (e.g., a tab) **315** extends laterally from the main axis so that each spring element **305** includes two opposite facing features **315**. The features **315** can have a feature length **320**, a feature proximal width **325**, and a feature distal width **330**.

FIG. **4** is a drawing illustrating a close up view of an implementation of a cross section of a spring element **305**. Each open element **310** has a diameter **335**. Each spring element **305** has an amplitude **340** that is the distance along an axis perpendicular to the main axis between the center of one open element **310** and the center of the other open element **310**. Each spring element **305** has a frequency **345**, which is the number of repetitions of spring elements over a unit distance (as measured along the main axis). The diameter **335** of each semicircular element **310** as well as the amplitude **340** and the frequency **345** of each spring element **310** can be varied to control characteristics of the flexible body **200** such as range of motion/deflection, spring constant, and resonant frequency.

FIG. **5** is a drawing illustrating a cross section of an implementation of flexible body **200** during an example deflection. The flexible body **200** can deflect in a lateral direction (relative to the cross section view). The deflection can be in a single direction (as shown in FIG. **5**), or in changing direction radially from a center line such as in a planar sine wave. Each feature proximal width **325**, feature distal width **330**, feature length **320**, spring element frequency **345**, spring element amplitude **340**, and spring element diameter **335** can be varied to control range of motion/deflection, spring constant and resonant frequency of the flexible body **200**. The range of motion/deflection, spring constant, and resonant frequency characteristics can be varied based on the intended application. For example, a UUV intended for longer distance but slow speed travel can include a flexible body **200** with a lower resonant frequency for increased propulsion efficiency than a UUV intended for shorter distance but higher speed travel.

FIG. **6** is a series of drawings illustrating an example implementation of a flexible body **200**. The flexible body **200** can include a cavity **350** along the main axis. At **610** is a top view of a portion of the flexible body **200** at rest (i.e. not deflected), at **620** is a top view of the flexible body **200** during deflection, and at **630** is a side (orthogonal) view of the flexible body **200** at rest (i.e. not deflected). In this example, the flexible body **200** and the cavity **350** are approximately conic.

FIG. **7** is a series of drawings illustrating an example embodiment of the flexible body **200**. At **710** is a top perspective of the flexible body **200** that further includes a fore-body interface **355**. The spring elements **305** with features **315** are shown as well as cavity **350**. In this embodiment, the features **315** length **320**, proximal width **325** and distal width **330** have been varied to give the flexible body **200** a biomimetic shape that could be considered approximately conic in shape and a smooth outer hydrodynamic surface. At **720** is a close up side perspective of several features **315**. The cavity **350** is also shown. At **730** is a top view of a portion of the example embodiment. The spring element amplitude **340** and frequency **345** are illustrated as well as the open element diameter **335**.

FIG. **8** is a series of drawings illustrating the example embodiment of the flexible body **200** mounted to a fore-body **120**. FIG. **8** includes an actuation system **205**, and a drive system **210**. The drive system **210** resides within the cavity **350** and can actuate or articulate to deflect the flexible body **200** in any planar shape desired. At **810** is a top rear perspective of the flexible body **200**. A portion of the drive system **210** is visible from this perspective. At **820** is a top view of the flexible body **200** attached to the fore-body **110**. The flexible body **200** is solidly attached at the posterior of the fore-body **110** and is located over the drive system **210** by its internal geometry but has slack for relative motion and for sliding along the drive system **210** if required.

The flexible body **200** can be composed of a material that is formed into the desired outer shape. In the example embodiments shown herein, the outer shape is conic, cylindrical, or mimics the shape of a posterior end of a tuna fish. The material can range from compliant material such as rubber and foam to non-compliant material such as steel. In one embodiment, the flexible body **200** is formed from a polyurethane composition. The material can include other compositions such as silicones and composites. When the flexible body **200** is attached to and around the drive mechanism intended to deflect a portion of the vehicle, whether for UUV propulsion, maneuvering, or braking, it deflects with the drive mechanism such that the outer shape follows the intended kinematic and hydrodynamic output of the drive mechanism's input. The features **315** are configured to account for length changes that occur during body flexure by providing relief along the length of the flexible body **200**. The series of spring elements **305** bend back and forth through the oscillatory motion, distributing the overall deflection of the motion across several spring elements **305**. The spring-like structure of the flexible body **200** allows it to be comprised of soft to stiff materials without encountering fracture, wear, or supplying unintended high reaction forces to the drive system. The amplitude **340** and frequency **345** of the spring elements along the length can be modified to optimize deflection forces as well as reduce reacted forces that are introduced into the system, thereby improving efficiency and smooth operation of the system. While the flexible body **200** in this example embodiment is attached at the posterior of the fore-body **120** and located over the drive system **210**, other configurations are possible.

Generally, the design and selection of the flexible body **200** spring elements, material properties, and dimensional properties enable the drive system to impart resonant and other frequencies into the flexible body **200**. This provides additional energy or propulsive capability via the flexible body's natural vibratory responses. Preferably, the flexible body **200** can be implemented as a single piece thereby improving ruggedness, flexibility, and resistance to compressibility, although the flexible body **200** can include multiple flexible elements and materials.

The flexible body **200** can be used for underwater or other media systems. By modification of the flexible body **200**, buoyancy can be adjusted. The spring elements **305** enable shape restoration (e.g., the flexible body **200** can regain its initial shape without input power from the drive system **210**). The flexible body **200** can also serve as a protective element by dampening impact from the external environment. It enables the generation of a smooth hydrodynamic or aerodynamic surface for efficient propulsion, maneuvering, and other operation within relevant environments. The flexible body **200** can also act as a mounting element for external functional, protective, and/or aesthetic skins (e.g., outer skin **215**). The flexible body **200** is shape independent in that it can be generated in many outside volumes and shapes (e.g., conic, cylindrical, etc.) while providing the functions above. The flexible body can function as a portion of the drive system, operating as the bending structure of the drive system and the outer volume (hydrodynamic shape) of the aft section.

Flexible body **200** has a number of advantages. For example, the flexible body does not have multiple moving mechanical parts that add drag, add weight, add cost, act as noise generators, or introduce individual vibratory modes (i.e. operates efficiently and quietly). The flexible body **200** can also have hydro-dynamically advantageous properties such as a smooth outer surface, integrated buoyancy, minimal weight, and minimal deflection and restoring forces. In one example embodiment, the flexible body **200** can be included in a flexible-bodied, biomimetic underwater vehicle to enable high maneuverability, high efficiency, and biomimetic propulsion and maneuvering. By distributing the loading and deflection via a series of small deflections incorporated within the flexible body **200**, propulsion efficiency of a flexible propulsor is improved.

A vehicle can include an aft section that floods when the vehicle is placed in liquid (e.g., water). By having an actuation system (located at least partially within the aft) capable of operating while submerged, the external environment can be leveraged to perform a thermal cooling function. When the actuator system is operated while at least a portion of the actuator system is submersed in liquid, the liquid serves to transfer thermal energy produced by the actuator system away from the actuator system.

By having an actuation system that can provide operation in a submerged state, the aft (e.g., tail, flexible aft) does not require seals, sealing features, sealing housings, and other like aspects. Infinite and omnidirectional heat sinking to the environment occurs such that actuator thermal power losses are reduced and the actuator can be driven at peak power levels (including, in some implementations, above power levels specified by manufacturers). The drive system can also operate while submerged.

Submersion of an actuator can apply to various technologies. For example, electromechanical actuators, Lorentz actuators, shape memory alloys, and artificial muscles.

FIG. **9** is a schematic illustrating an example of a fully assembled actuator **900**, which in some configurations can operate while submerged in liquid. The actuator **900** includes a bottom housing **910** and a top housing **915** coupled via a series of housing fasteners **921** (e.g., screws, bolts, etc.), bottom housing features **922** (shown at least in FIG. **10**A) and top housing features **923**. The bottom housing **910** includes side mounting holes **911** and pressure fittings **920** (show as NPT fittings). The top housing **915** can include at least one NPT plug **916** and top mounting hole **917**, and a main body. Mounted to the top housing **915** is a bearing housing assembly **965** via mechanical reduction fasteners **973** (e.g., screws, bolts, etc.). Output shaft **971** (e.g., rotational shaft) extends from the top housing **915**. Notably, the actuator **900** includes integrated mechanical speed reduction (in one implementation this is embodied as an integrated planetary gearbox inside a rotor) and can operate while flooded.

The actuator **900** is driven via a frameless prime mover (comprised of e.g., stator and rotor set and an integrated mechanical reduction in two housings). FIG. **10**A is a schematic illustrating an embodiment of the actuator bottom housing **910** assembly. FIG. **10**B is the schematic of FIG. **10**A with a portion of the bottom housing **910** assembly shown as transparent for illustrative purpose. A stator **925** is rigidly bonded or otherwise attached into the bottom housing **910**. The stator **925** is stationary and, in one embodiment includes an electromagnet comprised of field coils or windings for generating a magnetic field. The stator **925** can include other or different features commonly known in the field of electromagnetic actuation such as Lorentz actuators. The stator **925** is optionally coated to protect wiring and coils that comprise the stator **925** from exposure to water. The bottom housing **910**, which becomes integral with the stator **925**, is also the mounting location for the actuator's feedback sensor **930** (e.g., an encoder, resolver, hall effect sensor, back electromotive-force (EMF) sensor, etc.). The feedback sensor **930** measures the angular position of the driven magnetic assembly **946** (e.g., rotor assembly shown in, FIG. **11** and described in further detail below); provides feedback to both manage acceleration and speed and tune the actuator **900** for efficiency and other dynamics. The feedback sensor **930** can be mounted in the housing bottom **910** with its own mounting cup.

Feedback sensor **930** includes a feedback sensor housing **935**, sensor assembly mount **936** with mounting features **939**, an O-ring feature for optional face seal **937**, a sensor **940**, and a sensor wire guard **938**. The sensor **930** mounts to the bottom housing **910**. The sensor wire guard **938** overlaps the housing features **932** to protect the feedback sensor wiring **931**, and mounts to the bottom housing **910**.

The bottom housing **910** also contains features **932** to allow wire routing. Wires **931** from the feedback sensor **930** and from the stator **925** can run through features **932** (e.g., troughs, grooves, etc.) that lead to ports **933** (e.g. National Pipe Thread (NPT) or other) on the rear of the bottom housing **910**. These ports **933** can allow the wires **931** to exit the bottom housing **916** into a fitting **920**. A tube **934** (shown in FIG. **21**) can connect to each fitting **920** allowing the wires **931** to run to their destination.

FIG. **11** is a schematic illustrating a cutaway perspective of an embodiment of a driven magnetic device, in this case, the rotor assembly **945**. FIG. **16** is a schematic illustrating another perspective of the embodiment of the rotor assembly **945** shown in FIG. **11**. The top housing **915** locates a rotor assembly **945** into the top housing **915** and clamps down on the stator **925** to insure no movement during operation. The rotor **946** is bonded onto a rotor hub **947**. The rotor hub **947** incorporates an integrated iron-backing ring **948** to contain the rotor's magnetic fields, a sun gear **949**, and a sensor magnet **950**. The rotor hub **947** and sun gear **949** can be held together with a rotor spline **952**. The rotor spline **952** can allow for zero backlash and high torque transmission. The sensor magnet **950** integrates into the rotor hub **947** with a locating screw **951**, (e.g., a high-pitch locating screw). The sensor magnet **950** can be bonded into a bore in the locating mount **951**. This locating mount **951** allows the sensor magnet's **950** height to be finely adjusted by adjusting the locating mount **951**.

FIG. **12** is a schematic illustrating a cross section of an embodiment of the actuator **900** (shown without a planet carrier portion of a gearbox). The top housing **915** has a boss **961** in the middle in which the plantary gearbox's ring gear **955** is pinned to. A flanged rotor bushing **956** slides over the ring gear **955** and the boss **961**. The inner diameter of the rotor **946** rides on the rotor bushing **956**. The rotor bushing **956** material can be selected for hydrophobic properties. Along with the rotor bushing **956**, the rotor assembly **945** is located by a thrust bushing **957**. The thrust bushing **957** can also be made of hydrophobic material. The thrust bushing **957** can serve as a buffer between the bottom housing **910** and the rotor hub **947**. Spring pins **959** locate the ring gear **955**.

FIG. **13**A is a schematic illustrating an embodiment of a mechanical reduction assembly **965** (e.g., planetary gearbox). The top housing **915** locates the bearing housing **977**, mechanical reduction **967**, and mechanical reduction carrier **966**. In this embodiment, the planetary gearbox **965** includes three planet gears **967**, which hold relative to each other on the mechanical reduction **966**. As in FIG. **13**B, the planet gears **967** have a shaft **970**. The shaft **970**, along with bushings **968** and snap ring **969**, attaches the gears **967** to the mechanical reduction **966**. The mechanical reduction **966** includes output shaft **971**, and spline **972**.

FIG. **14** is a schematic illustrating an embodiment of an assembled mechanical reduction **965** and bearing housing assembly **975**. The mechanical reduction assembly **965** mounts into a top housing plate **977** with a bearing housing **976**. In this embodiment, the bearing housing **976** contains two stainless steel ball bearings **978** separated by bearing spacer **983**. The ball bearings **978** locate the mechanical reduction **966** and allow the output shaft **971** (planet shaft) to spin with minimal loss during actuator **900** operation. The bearing housing **976** passes through the top plate **977** and affixes to the top housing **915** with its flange **979**. The mechanical reduction **966** holds in place with a snap ring **980**. The bearing housing assembly **975** further includes an optional rotary seal cap **981**, and features for an optional rotary seal **982**. Additionally, the bearing housing assembly **975** includes features for optional O-rings **985** for integration with the top housing **915**, and a sealing screw location **984** (for providing access for sensor adjustment).

FIG. **15** is a schematic illustrating a cross section of an embodiment of a fully assembled actuator **900**.

In the illustrated embodiments, when the actuator **900** is operated, the rotor **946** spins relative to the fixed stator **925**. The rotor **946** spinning causes the planetary gearbox **945** to spin through the coupling of the rotor **946** and the sun gear **949**. The planetary gearbox **965** translates the rotation of the rotor **946** into a rotation of the output shaft **971** that rotates at a reduced rate but increased torque, thereby increasing the torque of the actuator **900**. The example embodiment shown has a planetary gearbox **965** ratio of **4.4:1**, although multiple ratios are possible and contemplated.

All the external components of the example embodiment are implemented in with O-rings, NPT ports, and an output shaft rotary seal if required (they can be required for operating sealed or for testing, pre-use). In one embodiment, the actuator **900** has two side mounting holes **911** and seven top mounting holes **917** arrayed in a circular pattern. The top mounting holes **917** can enable an optional addition of an external gear reduction (not shown). A port **916** on the top housing **915** can drain the actuator **900** if the actuator **900** is run flooded or for seal testing the actuator **900** if it runs dry. If the actuator **900** is to be run flooded, the tubes **934** carrying the wires **931** from the actuator **900** can be potted or plugged.

The actuator **900** described herein has a number of advantages. For example, rotating components are supported by bearings, bushings, and features of appropriate materials combined with the alignment of the actuator **900** components and the feedback sensor **930** to enable the actuator **900** to operate with minimal friction. The bushings (e.g., rotor bushing **956** and thrust bushing **957**) configure such that there is little or no swelling of the material when operating in water (swelling increases drag and potentially jams the actuator **900**). Rapid, accurate replacement, or variation in the feedback sensor **930** is enabled by this design. The housing, seal, and ports allow the actuator **900** to be sealed and run dry or operated with an internal oil bath for pressure compensation (e.g., in a deep underwater application) and optionally lubrication. The mechanical reduction output shaft's **971** end has a spline **972** for minimal backlash and high torque transmission. The inner components are designed to provide low backlash and high accuracy for efficient propulsion when used in the UUV embodiment.

Additionally, removal of coulomb friction and stiction enables highly efficient oscillatory operation of the drive system **210** under varying loads with varying outputs. The actuator **900** has a slim profile (while still including a frameless motor, feedback sensor **930**, supports (i.e. bearings **978**), and mechanical reduction (i.e., gearbox)). Since the actuator **900** can be run submerged (e.g., under water), it can take advantage of a cooler ambient environment temperature to perform heat removal and regulation improving power output. Additionally, mechanical losses in the actuator **900** are minimized and the multiple function actuator **900** housing (i.e. bottom housing **910** and top housing **915**) incorporates environmental cooling, active liquid cooling, seal testing, and oil-based pressure compensation. Further, the actuator **900** includes highly accurate output and adjustability for tuning the actuator **900**.

Multiple actuators **900** can combine to form an actuation system **1700** (or actuation stack). FIG. **17** is a schematic illustrating an example "stack" of actuators **1700** in a support stack **1705**. The stack can be of submersible linear actuators or nonconventional actuators. In one embodiment, the actuation stack **1700** enables a concentrated multiple axis actuator stack that is suitable for efficient operation and control of an underwater vehicle. In one embodiment, the actuators **900** couple with the drive system **210** such that each actuator **900** can articulate a joint in the drive system **210**. The actuators **900** work in concert to control overall flexible aft **120** motion.

The actuator stack **1700** can be placed at the anterior end of the propulsion system. The propulsion system refers to the following components: actuator stack **1700**, drive system **210**, flexible body **200**, and propulsive element **220**. In the example embodiment shown in FIG. **17**, six actuators **900** are stacked vertically and configured to interface with the drive system **210** (not shown in FIG. **17**). The propulsion system support stack **1705** includes main body **1711** (or interface support), support stack covers **1707**, and connection block **1720**. Each actuator **900** can fit into a respective groove **1708** on the interface supports **1711**. The actuator **900** can be attached to features **1710** in the interface supports **1711** via fasteners **1709** (or quick connect hardware). The actuator **900** wiring **931** runs to the interface supports **1711** through tubes **934** (shown in FIG. **21**) and can connect to terminal blocks **1712** (shown in FIG. **20**) inside each interface support **1711**. This configuration enables individual actuators **900** to be removed from the stack **1700** for maintenance or replacement. To remove an actuator **900** from the stack, the associated wires **931** are disconnected from the terminal blocks **712** and the actuator is pulled out of the stack **1700** thereby pulling the associated wires **931** through the tubing **934**.

The actuator stack **1700** interfaces with the fore-body **120** of the vehicle through two bore seals **1713**. These bore seals **1713** are integrated into the actuator stack's interface supports **1711**, which enclose the wiring **931**, and into mating connector blocks **1720** that are secured to the fore-body **120**. The mating connector blocks **1720** are secured to the fore-body **120** with fasteners **721**, and are open to the inside of a pressure hull of the vehicle fore-body **120** through face (or bore) seals. The connector blocks **1720** are detachable from the fore-body **120** but detachment is not required for integrating or swapping the propulsion system.

FIG. **18** is a schematic illustrating a cutaway perspective of an example implementation of a connector block **1720**. Inside the connector blocks **1720** and the interface supports **1711** are mechanical guides and electrical connectors **1722**. The connectors **1722** connect the wiring **931** of the actuator stack **1700** to the fore-body's **120** electronics. The fore-body's **120** electronics package can include one or more of any of the following: a mission controller, a vehicle controller, motion controllers, power system, data acquisition system, communications, and an energy source. In some embodiments, the fore-body **120** can include temperature sensors, pressure sensors, radio module, GPS, speed sensors, one or more Ethernet ports, depth sensing, and related equipment. The electrical connectors **1722**, in this embodiment, include four sets of connectors, two in each bore seal **1714**. The connectors **1722** mounted in the interface supports **1711** fix in place, while the connectors **1722** in the connector blocks **1720** are allowed to float slightly. The connectors **1722** can align together during connection of the fore-body **120** and flexible aft **110** through a locating or alignment feature **1723** (e.g., pin) on the actuator stack **1700**. The floating connector **1722** allows for slight misalignment in attaching the actuator stack **1700** to the fore-body **120**.

FIG. **19** is a schematic illustrating a close up perspective of an example actuator stack **1700** including interface support **1711** and connector blocks **1720**. FIG. **20** is a photograph of an example embodiment illustrating terminal blocks **1712**. FIG. **21** is a photograph of an example embodiment illustrating a rear perspective of the actuator stack **1700**. FIG. **22** is a diagram illustrating some advantages of a modular UUV in accordance with the current subject matter. The flexible aft **110** is modular and can be removed or exchanged for an alternative flexible aft **110**. For example, FIG. **23** is a photograph illustrating an alternative flexible aft **110** embodiment wherein the propulsive element **220** includes not only a foil, but also a thruster. Another alternative embodiment includes additional fore-body **120** payload volume. Thus, different flexible aft **110** sections can be easily changed based on the intended application or mission parameters.

The actuator stack **1700** and support stack **1705** provide many advantages. For example, they enable the propulsion system to be removed from the fore-body **120** rapidly, with minimal work, with low risk of component damage, and without disruption of existing wiring. Wiring as used herein can include flex-circuits or other comparable alternatives. The modularity of the propulsion system provides for the ease of: flexible-aft **110** replacement (swap out) for mission specific operation; development improvements and debugging; system assembly and integration; maintainability; testing; advances; and reparability.

Additionally, the actuator stack **1700** and support stack **1705** system provides several redundant layers of protection for sensitive electrical components and thereby saves cost of waterproofing the cabling and electrical connections going into the fore-body **120**. This enables off the shelf, non-wet connectors to be used instead of wet cables. Wet cables are expensive, often have very limited number of times to make and break connections, and options are limited. Cables have to be vetted and molded, adding cost and lead-time. Dry connectors are far less expensive, easier to come by, smaller, and there are many varieties available. Further, there are more failure points in systems with wet cables and bulkheads. In that case, each bulkhead must be water tight to the hull along with the seal between the bulkhead and the cable running to the other system. As such, there are more places and thus more opportunity for water ingress and system damage. Some embodiments of the current subject matter have just two bore seals to connect the two systems.

The fore-body **120** and the flexible aft **110** can be pressure or vacuum tested as a whole rather than independently (such as when wet cables are used) because the two system's air volumes are not connected in the latter. In other words, both systems no longer have to be seal-checked separately prior to use. Connected air volumes reduce the requirement for multiple internal health sensors that monitor the status of vehicle conditions, like temperature, pressure, and potential leaks. If the two air volumes are connected, only one set of these health sensors are required.

Although a few variations have been described in detail above, other modifications are possible. Other embodiments may be within the scope of the following claims.

What is claimed is:

1. A flexible body comprising:

a spring body including a spring element extending along a main axis, the spring element comprising two opposed semicircular portions formed in an S shape;

features extending in a second axis perpendicular to the main axis and defining an outer shape;

a cavity within the spring body and the one or more of the features.

2. The flexible body of claim **1**, wherein the features extending in the second axis comprise tabs, each feature integral with a corresponding semicircular portion such that each spring element has at least two opposite facing features.

3. The flexible body of claim **1**, wherein the outer shape is biomimetic, conic, or cylindrical.

4. The flexible body of claim **3**, wherein the features taper along the main axis.

5. The flexible body of claim **1**, wherein the spring body comprises a plurality of spring elements, and one or more attributes of the spring elements vary among the spring elements, the attributes including one or more of shape, amplitude, frequency, materials, and thickness.

6. The flexible body of claim **5**, wherein the attributes vary such that when deflected, the flexible body moves in a biomimetic motion.

7. The flexible body of claim **1**, wherein the cavity extends the entire length of the spring body.

8. The flexible body of claim **1**, wherein the cavity extends through a partial length of the spring body.

9. The flexible body of claim **1**, wherein the cavity includes a plurality of discreet cavities.

10. The flexible body of claim **1**, wherein at least a portion of a drive system resides within the cavity.

11. The flexible body of claim **1**, wherein the flexible body forms a flexible frame structure for a drive system contained at least partially within the cavity.

12. The flexible body of claim **1**, wherein the flexible body is attached to a fore-body.

13. The flexible body of claim **1**, wherein each spring element is biomimetic.

14. An aquatic vehicle comprising:

a fore-body;

an aft section;

an actuator system at least partially within the aft section; and

wherein, the aft section is configured such that, when the aquatic vehicle is within liquid, at least a portion the aft section is flooded with liquid such that at least a portion of the actuator system is submerged and the actuator system is configured such that, when the actuator system is operated while at least a portion of the actuator system is submersed in liquid, the liquid serves to transfer thermal energy produced by the actuator system away from the actuator system.

15. The aquatic vehicle of claim **14**, wherein the actuator system comprises:

a top housing;

a bottom housing affixed to the top housing comprising a main body, a feedback sensor, a stator, and a thrust bushing;

a rotor assembly disposed within the bottom housing and top housing, the rotor assembly comprising a rotor, a rotor hub, and a rotation element;

a mechanical reduction assembly disposed within the bottom housing and top housing, coupled to the rotor assembly rotation element, the mechanical reduction assembly comprising a mechanical reduction, one or more rotation elements, and an output shaft; and

a bearing housing assembly affixed to one of the top housing and bottom housing, providing for a rotation of the mechanical reduction, the bearing housing assembly comprising a bearing, and a bearing housing.

16. The aquatic vehicle of claim **15**, wherein an electrical current applied to the stator causes the rotor assembly to rotate around the rotor hub, thereby causing the mechanical reduction output shaft to rotate.

17. The aquatic vehicle of claim **15**, wherein the rotor assembly rotational element is coupled to the one or more mechanical reduction rotational elements such that a rotation of the rotor imparts a rotation to the mechanical reduction.

18. The aquatic vehicle of claim **15**, wherein the actuator system includes ports and features to enable seal testing.

19. The aquatic vehicle of claim **14**, wherein, when the aquatic vehicle is submerged in liquid, the aft allows liquid to move between an interior and exterior of the aft, the exterior of the aft including an external environment.

20. The aquatic vehicle of claim **14**, wherein the aft comprises a flexible body.

21. An aquatic vehicle comprising:

a fore-body,

an actuation system connected to the fore-body;

a drive system comprising a plurality of flexure points and actuated by the actuation system; and

a flexible body attached to the fore-body and enclosing at least a portion of the drive system, the flexible body comprising:

a spring body including a spring element extending along a main axis; and

a cavity within the spring body;

wherein the actuation system comprises:

an actuator;

one or more interface supports having features, electrical connections, a seal, and the actuator being secured to the features; and

one or more connector blocks connected to the fore-body and the interface supports.

22. The aquatic vehicle of claim **21**, wherein an outer shape of the vehicle is biomimetic, conical, or cylindrical.

23. The aquatic vehicle of claim **21**, wherein the vehicle is configured for biomimetic propulsion.

24. The aquatic vehicle of claim **21**, wherein each actuator comprises:

a top housing;

a bottom housing affixed to the top housing comprising a main body, a feedback sensor, a stator, and a thrust bushing;

a rotor assembly disposed within the bottom housing and top housing, the rotor assembly comprising a rotor, a rotor hub, and a rotation element;

a mechanical reduction assembly disposed within the bottom housing and top housing, coupled to the rotor assembly rotation element, the mechanical reduction assembly comprising a mechanical reduction, one or more rotation elements, and an output shaft; and

a bearing housing assembly affixed to one of the top housing and bottom housing, providing for a rotation of the mechanical reduction, the bearing housing assembly comprising a bearing, and a bearing housing.

25. The aquatic vehicle of claim **21**, wherein the actuation system can disconnect from the fore-body.

26. The aquatic vehicle of claim **25**, wherein a second and different actuation system can connect to the fore-body.

27. The aquatic vehicle of claim **21**, wherein the drive system comprises:

a body with one or more flexible points in the body;

first connectors coupled to the actuation system at a first end; and

second connectors coupled to a propulsive element at a second end.

28. The aquatic vehicle of claim **21**, further comprising a propulsive element located at a posterior end of the vehicle.

29. The aquatic vehicle of claim **28**, wherein the propulsive element comprises one or more of: foil, thruster, and water jet.

30. The aquatic vehicle of claim **21**, wherein the flexible body defines a volume, and when the aquatic vehicle is submerged in liquid, a portion of the volume is flooded with the liquid such that, at least a portion of one or more of the actuation system and the drive system is submerged.

31. An aquatic vehicle comprising:

an actuation system connected to the fore-body;

a drive system comprising a plurality of flexure points and actuated by the actuation system; and

a flexible body enclosing at least a portion of the drive system, wherein the flexible body defines a volume, and when the aquatic vehicle is submerged in liquid, a portion of the volume is flooded with the liquid such that, at least a portion of one or more of the actuation system and the drive system is submerged.

32. An aquatic vehicle comprising:

a drive system comprising a plurality of flexure points;

a flexible body comprising a spring-body including a spring element extending along a main axis, and a cavity within the spring body enclosing at least one flexure point, the flexible body including a resonant frequency of oscillation; and

an actuation system configured to actuate the drive system at the resonant frequency for propulsion.

33. The aquatic vehicle of claim **32**, wherein the actuation system is tuned for efficiency.

34. The aquatic vehicle of claim **32**, wherein the actuation system is tuned for dynamics.

35. The aquatic vehicle of claim **32**, wherein the actuation system provides feedback for managing acceleration and speed.

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